Phase I – Final Report

Enabling All-Access Mobility for Planetary Exploration Vehicles via Transformative Reconfiguration

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Executive summary

Effective large-scale exploration of planetary surfaces requires robotic vehicles capable of mobility across chaotic terrain. Characterized by a combination of ridges, cracks and valleys, the demands of this environment can cause spacecraft to experience significant reductions in operating footprint, performance, or even result in total system loss. Significantly increasing the scientific return of an interplanetary mission is facilitated by architectures capable of real-time configuration changes that go beyond that of active suspensions while concurrently meeting system, mass, power, and cost constraints.

This Phase 1 report systematically explores how in-service architecture changes can expand system capabilities and mission opportunities. A foundation for concept generation is supplied by four Martian mission profiles spanning chasms, ice fields, craters and rocky terrain. A fifth mission profile centered on Near Earth Object exploration is also introduced. Concept generation is directed using four transformation principles - a taxonomy developed by the engineering design community to explain the cause of an architecture change – and existing brainstorming techniques. This allowed early conceptual sketches of architecture changes to be organized by the principle driving the greatest increase in mission / performance capability.

Thirty-one concepts (12 using expand / collapse, 6 using expose / cover, 6 using fuse / divide, and 7 using reorientation) are presented in Section 2. For each concept, the idea behind the design is explained, the primary transformation facilitator is identified, proposed advantages and disadvantages of the configuration change are highlighted, and ramifications on system architecture are explored. Lessons learned from this systematic study are that:

- The principle of fuse / divide is mainly facilitated by segmentation and modularity. When used alone at the system level, this type of architecture change often results in two independent systems that must be designed and evaluated, and has limited ability to revolutionize planetary rover design. However, when this principle is linked with other principles, game-changing architecture changes become possible.
- Reorientation often serves a secondary role. However, this principle can enable game-changing architecture changes when combined with other transformation principles.
- The principles of expand / collapse and expose / cover serve as the main drivers of significant performance modification.
- Reconfigurability is of greatest impact when responding to localized operational changes. One-time configuration changes accommodate mission phase transitions.
- The lack of orthogonality between transformation principles highlights that the most innovative solutions with the greatest change of performance benefits come from concepts that blur the lines between principles (or use multiple principles).

A second objective of this report is to explore how physical and virtual prototypes can lead to rigorous assessment and validation of the proposed concepts. Three architectures are developed in Section 3 that were selected by the research team using the conclusions from the systematic study in Section 2. In choosing the system architectures develop, the team considered:

- Diversity of targeted missions within the product portfolio;
- Concepts requiring multiple transformations (one-time and reconfigurable);
- Concepts that blurred the line between transformation principles and facilitators.

For each concept, a generalized mission profile is introduced and the required architecture changes are discussed in an operational context. The analyses conducted to assess initial technical feasibility are presented, and critical path technical challenges / questions are highlighted.
The work in Section 3 allows for initial parameters of system architecture to be explored. However, measuring system performance across chaotic terrain requires a system-level simulation. Section 4 presents a strategy for assessing the effectiveness of an architecture transformation when chaotic terrain is considered. A hi-fidelity simulation environment is used to quickly run a myriad of test scenarios on a concept presented in Section 3.2 and a traditional rocker-bogie architecture. Four rovers – two architectures using two size scales - are tested in twenty terrain scenarios, and their performance is explored across various levels of ground traction, slope, and rock field density. Utility theory is combined with identified performance measures to explore rational architecture selection across potential missions generated as a combination of terrain scenarios.

The analyses in section 4 provide insight into the relative strengths of the four designs in a variety of scenarios. The transformative architecture generally underperforms the rocker bogie at traditional rover tasks. This is largely because the rover's ability to reconfigure to a spherical mode imposes substantial constraints on the architecture of its rover mode. However, it is this ability to transform that gives the system a distinct and significant advantage over the rocker bogie rover when it is used for downhill travel. Thus, architecture decisions for a given mission must be based on mission profile, terrain encountered, and general size requirements as necessitated by mission objectives of the rover to be deployed.

Finally, the report offers a list of dissemination efforts and final conclusions.

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1. Introduction

Effective large-scale exploration of planetary surfaces requires robotic vehicles capable of mobility across chaotic terrain. The evolution of these vehicles from lander to rover has traditionally encompassed wheeled designs with architectures that represent "active suspensions." This "rocker-bogie" style architecture has been used to provide a degree of responsiveness in difficult terrain. For example, *Spirit* and *Opportunity* were designed to handle obstacles (rocks and holes) slightly larger than their wheel diameter of 10 inches (JPL 2011). Albeit much larger, the Lunar Rover Vehicle was capable of navigating obstacles one foot high, crossing crevasses 28 inches wide, and climbing slopes as steep as 25 degrees (Boeing 1971).

While these capabilities are impressive, a traditional architecture may not be the most effective design decision for extreme environments that are widely varying and have uncertain conditions. The inability to adapt in these extreme environments can lead to significant reductions in operating footprint, performance, or at worst the total loss of the system. This was demonstrated when *Opportunity* became immobilized after its wheels sank into an unexpectedly soft Martian soil type. Yet, an even greater challenge when designing planetary vehicles for large-scale exploration is 'chaotic terrain' – areas characterized by a combination of ridges, cracks, and valleys, as shown in Figure 1.

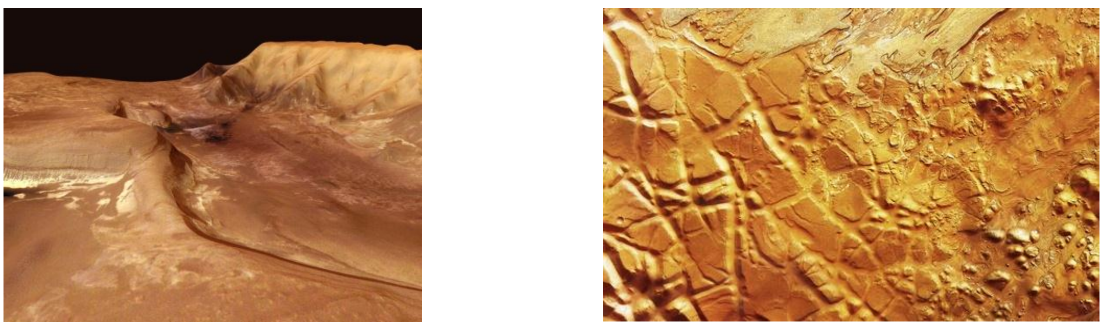


Figure 1. Examples of chaotic terrain on Mars

Considerable research has been done in recent years to improve the sensing and control aspect of planetary exploration vehicles (Kean 2010, McGovern and Wagstaff 2011). However, significantly increasing the scientific return of an interplanetary mission may best be facilitated by developing new technologies that fundamentally re-envision the architecture around which these systems are built. Traversing chaotic terrain may be better met by systems capable of real-time configuration changes that go beyond that of an active suspension while concurrently meeting system, mass, power, and cost constraints.

The central objective of this Phase 1 effort was two-fold. The first goal was to systematically explore how architecture changes after deployment could expand system capabilities and mission opportunities. Where possible, reconfigurable configuration changes were identified and explored. Reconfigurability, in this context, was constrained to the physical (hardware) domain and characterized as repeatable and reversible changes to system architecture after the system has been deployed (Ferguson et al. 2007, Olewnik et al. 2004). The second goal of this effort was to explore how physical and virtual prototypes could lead to rigorous assessment and validation of the proposed concepts. From the original Phase 1 proposal, the following objectives were proposed:

- Generate configuration changes using transformation principles and brainstorming sessions,
- Identify concepts that use transformation for further development;

- Create virtual and physical prototypes;
- Develop analytical models describing system motion / configuration change;
- Generate multiple random terrain profiles;
- Conduct a quantitative evaluation of system performance.

The remainder of this report is presented in four distinct sections. Section 2 describes the effort to generate and explore system concepts by using transformation principles. Three system architectures are selected and discussed in further detail in Section 3. Section 4 highlights efforts to further develop rigorous methods for quantifying and validating the performance of a reconfigurable system. Finally, Section 5 discusses overall conclusions from this study and highlights opportunities for future work.

2. Conceptual development and initial exploration of the solution space

Increasing the TRL associated with transformative configuration changes in planetary exploration vehicles requires understanding the necessary technologies that must be developed. To begin this investigation, concepts are required that define the way in which a spacecraft is allowed to physically change form. From a designer's perspective, it is not reasonable to expect that any two points from the problem's design space are achievable configurations. In this work, transformation principles and facilitators will be used to generate concepts that guide how the spacecraft "moves" between states.

Section 2.1 introduces and defines the transformation principles and facilitators that have been identified by the engineering design community. These principles are characterized by exploring analogies found in nature, patents, and marketed products. To provide perspective on the direction of concept generation, potential missions identified by the research team that demands in-service configuration changes are described in Section 2.2. Section 2.3 presents and discusses the conceptual designs created using each transformation principle. Finally, Section 2.4 concludes with a discussion of the major insights gained from this research path.

2.1 Introduction

In the last few years, research within the engineering design community has begun to explore the benefits of reconfigurable and changeable systems. Driven by the inherent tradeoffs that must be navigated in a multiobjective design problem, the need to accommodate multiple abilities has been a steering force behind much of this research (Olewnik et al. 2004; Siddiqi et al. 2006; Ferguson et al. 2007). Interest in this area has also increased with a desire to achieve engineered resilience (Neches 2011; Madni and Jackson 2009). The definition of resilience in this context characterizes a system's ability to affordably adapt and effectively perform across wide ranges of operational contexts through reconfiguration or replacement. Initial efforts in this area of research began with parameter studies (Martin and Crossley 2002; Bowman et al. 2002), multiobjective formulations to allow for optimal end-state determination (Ferguson et al. 2008; Olewnik et al. 2004; Olewnik and Lewis 2006; Khire and Messac 2008; Chmarra et al. 2010; Bowman et al. 2002), and the development of probabilistic models to predict when state modifications should occur (Siddiqi and de Weck 2008; Arts et al. 2008). More advanced techniques have relied on the assignment of cost data (Olewnik et al. 2004; Olewnik and Lewis 2006), modular expansion (Lewis and Mattson 2011; Lewis et al. 2011; Chmarra et al. 2008; Pate et al. 2011; Patterson et al. 2011), product family generation (Simpson et al. 2006; Jiao et al. 2007; Pirmoradi and Wang 2011) and the generalization of a linear tracking control scheme with assumed system dynamics (Ferguson and Lewis 2006).

While these efforts rely on a numerical exploration of changeability, the direction of this work is more in line with those proposed by McGowan et al. (2009), who state the need to "consider that there are many methods to transform or change the vehicle to achieve the same performance objective." They continue, stating that a "better strategy would be to highlight the increased capability … and seek the best methods to enable it." Research designed to aid in the brainstorming and early conceptual phases of design has led to the identification of four transformation principles (Singh et al. 2009; Haldaman 2010; Haldaman and Parkinson 2010): expand/collapse, fuse/divide, expose/cover, and reorientation. These principles fundamentally explain how systems change their configuration, with example applications shown in Figure 2.

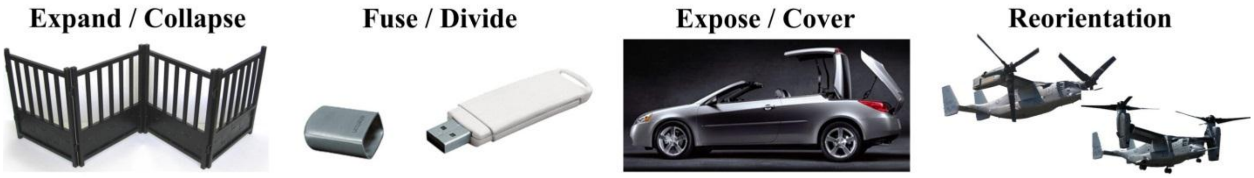


Figure 2. Transformation principles

The expand/collapse principle involves changing physical dimensions of an object to bring about an increase or decrease in occupied volume. The fuse/divide principle involves transforming between a single functional device and two or more component devices. Here, at least one of the component devices has its own distinct functionality. The expose/cover principle involves exposing or covering components or surfaces to alter functionality. Finally, the reorientation principle creates a new system configuration by reorienting an aspect of the system in a new way.

Alone, the principles describe the cause of the transformation. They do not describe what makes the transformation function in a correct manner. Transformation facilitators, as shown in Figure 2, have also been defined to address this need. These facilitators are design constructs that help or aid in creating the mechanical transformation. However, they must be linked to a transformation principle in order to actually enact physical change.

To direct concept generation using these principles and facilitators, work began by selecting missions that would pose significant challenges to rovers built around the traditional rocker-bogie architecture. This is the focus of the next section.

Principles	Expand/Collapse	Change physical dimensions of object along and axis, in a plane, or in three dimensional space
	Expose/Cover	Expose/Cover a new surface to alter functionality
	Fuse/Divide	Make single functional device become two or more devices, at least one of which has its own distinct functionality defined by the state of the transformer or vice versa
Facilitators	Common core structure	Compose devices with a core structure that remains the same, while the periphery reconfigures to alter the function of the device
	Composite	Form a single part from two or more parts with distinct functionality
	Conform with Structural Interfaces	Statically or dynamically constrain the motion of a component using structural interfaces
	Enclosure	Manipulate object in two or three dimensions in order to enclose a three dimensional space
	Flip	Perform separate functions based on orientation of the object
	Function Sharing	Perform two or more discrete functions
	Furcation	Change between two or more discrete stable states determined by boundary conditions
	Generic Connections	Employ internal or external connections (structural, power) that can be used by different modules to perform different functions or perform the same function in a different way
	Interchangeable transmissions	Use multiple transmissions to produce different motions
	Material Flexibility	Change object dimensions with change in boundary conditions
	Modularity	Localize related functions utilizing common signal, material, and force flows into subsystems (modules) which are easily integrated into the device and may be interchangeable
	Nesting	Place an object inside another object wholly or partially wherein the internal geometry of the containing object is similar to the external geometry of the contained object
	Segmentation	Divide single contiguous part into two or more parts
	Shared Power Transmission	Transmit power from a common source to perform different functions in different configurations
	Shelling	Embed functional element in a device which performs a different function

Figure 3. Transformation principles and facilitators

2.2 Mission suite identification

To provide a foundation for concept generation, five different mission profiles were selected and explored. This section provides a brief discussion of each mission concept.

<u>Exploration of Valles Marineris</u>

Valles Marineris is an extensive system of canyons along Mars's equator. It is over 400km long, up to 7km deep and up to 200km wide (NASA). This mission profile is designed to explore Valles Marineris, with a proposed landing site located in a crater at the head of the canyon, as shown in Figure 4. This site is valuable because exploring the canyon walls provides an opportunity to investigate the stratigraphy of Martian rock, directly addressing Mars Exploration Program Analysis Group (MEPAG) Goals II.C.2 and III.A.1 (MEPAG 2010).

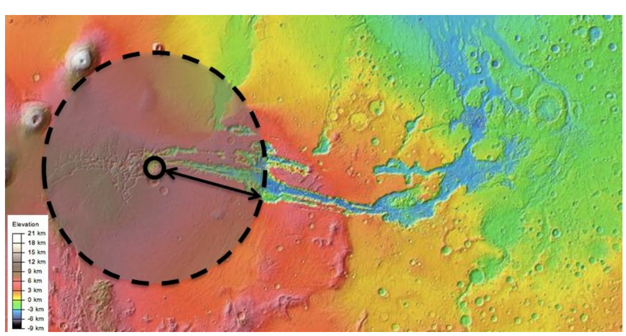


Figure 4. Valles Marineris and surrounding regions

Exploration of Hellas Basis

This mission profile is designed to facilitate planetary exploration of locations that have flat areas, gentle gradients and steep slopes. This location is particularly attractive, as traditional rocker-bogie architectures have difficulty maneuvering down steep slopes. Example exploration sites comprised of such terrain are the Hellas Basin, as shown in Figure 5, and the Tharsis region. A landing site is chosen that is at an elevated altitude relative to the planned mission path. In the Hellas Basin, the landing site selected is at the edge of the crater. The mission path is hundreds of kilometers long, since the basin is over 2000 km in diameter and 8 km deep.

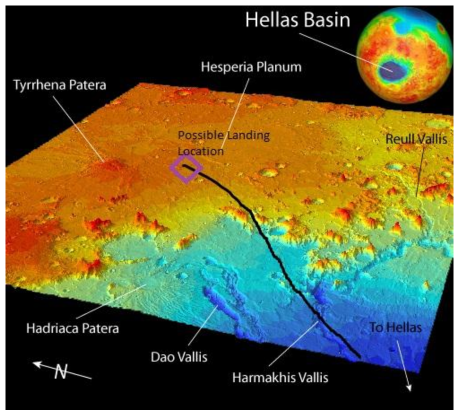


Figure 5. Hellas Basis topography

Exploration of Melas Chasma

Melas Chasma is the largest single feature in the Valles Marineris and was considered as a landing site for the Mars Pathfinder and Mars Exploration Rover missions. The large (visible from orbit) channels in the chasm seems to have been cut by flowing water and the sulphate deposits around it may indicate a former lake. Melas Chasma also drops down nearly 9km, making it one of the lowest depressions on the planet and adding to its scientific value by offering one of the most comprehensive views of Martian geological history. Using an aerial vehicle to study this chasm would be complicated by 25 m/s wind jets along the surface and 5 m/s vertical winds down the walls during the evenings. These high wind speeds as well as the relative lack of unobstructed landing sites are among the reasons Melas Chasma has not been chosen as a landing site previously.

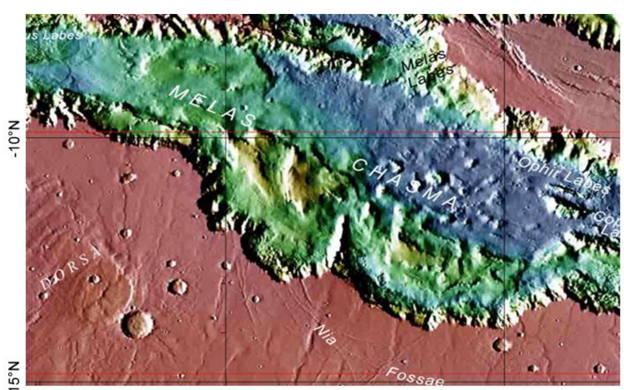


Figure 6. Melas Chasma

Exploration of the Chasma Boreale

Chasma Boreale is a large canyon located within the Mare Boreum in Mars' northern polar region. The chasm is roughly the size of the Earth's Grand Canyon at 560km long, 60km wide and up to 2km deep. This area is of significant scientific interest since the chasm appears to be older than the ice sheet of the Mare Boreum, as evidenced by the still present craters on its floor. The Martian pole experiences significant seasonal temperature variations that result in carbon dioxide subliming to gas during the summer and solidifying into 'snow' during the winter. A rover landed near the mouth of the chasm could not practically be expected to travel a significant fraction of the canyons length during a single season and would have to be designed to survive the -145°C winter. The Phoenix Lander is the only craft to have been sent to the Martian polar region and communication with it was lost during its first winter.

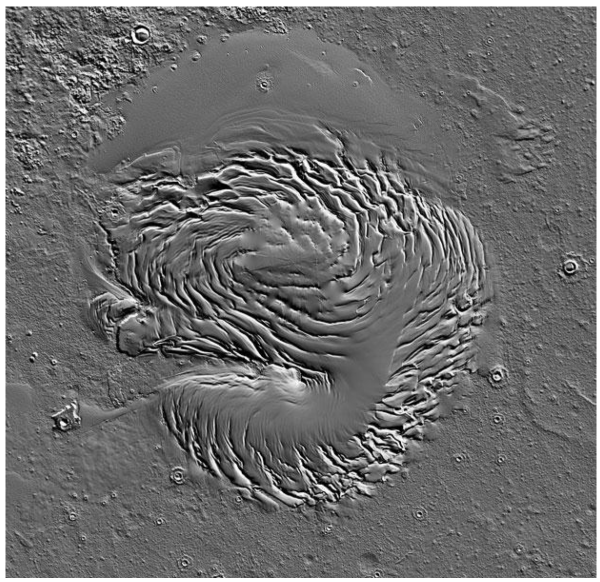


Figure 7. Mare Boreum region of Mars. Chasma Boreale is the large feature in the lower left that divides the region into two sections. (Image: NASA/GSFC)

Exploration of Near-Earth Objects

Asteroid missions have been of increasing interest over the past decade. Asteroids offer great scientific value; they are remnants of the beginning of the solar system that have remained relatively unchanged since they do not have atmospheric processes. They also offer a relatively easy target for sample return missions, which have seen a resurgence in popularity over the past several years. Asteroids have been sparsely studied close up and missions to land on them have been only moderately successful. The Russian Phobos-Grunt mission to Mars' small moon Phobos (which is very likely a captured asteroid) failed to land successfully. The recent Japanese Hayabusa mission to 25143 Itokawa was a mixed success; it returned a sample to Earth but its hopping rover failed to deploy. The extreme low gravity of most asteroids makes them difficult to explore, wheels cannot get traction and hopping rovers could inadvertently escape the asteroid. Gravity also tends to be inconsistent as asteroids can have highly irregular shapes. Furthermore, high spin rates can cause centripetal acceleration to cancel out gravitational influence completely.

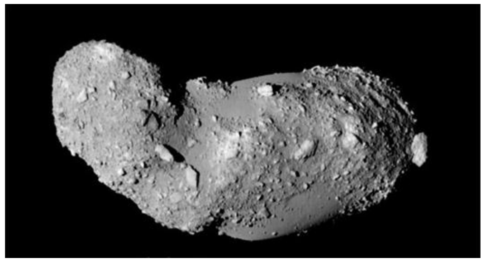


Figure 8. 25143 Itokawa (Image: JAXA)

Having defined possible mission profiles, concepts leveraging configuration changes were then generated. The goal of the study became understanding ***when*** in-service configuration changes could be useful, possible technological limitations, and the ramifications with regards to system architecture. This is discussed in the next section.

2.3 Concept generation and initial discussion

Prior efforts found in the literature that embed a degree of reconfigurability in planetary exploration vehicles can be classified using transformation principles. For example, researchers have explored flexible wheels that use the principle expand/collapse to maximize traction while minimizing wheel slippage for different soil types (Favedi et al. 2011, Siddiqi et al. 2006). Controlling these changes has led to schemes that minimize a cost function dictated by velocity / chassis configuration (Furlong et al. 2010) and an active control problem that improves stability and traction in wheel-legged robots (Freitas et al. 2009). Researchers have also explored reconfigurations that allow for a hybrid leg-wheel robot (Rhomer et al. 2010). In this work, a switching strategy is defined that determines when wheel or leg-based locomotion modes are active. Efforts have also extended to robotic teams, combining a manipulator, rover, and climbing robot under the principle fuse/divide (Cordes et al. 2009). Fuse / divide also enables PolyBot to have a self-reconfigurable modular robotic architecture where multiple identical modules are created that can be rearranged after deployment (Yen et al. 2003).

Having previously defined regions of Mars and other bodies where chaotic terrain exists, the next step was to generate concepts that leveraged system transformations to facilitate terrain exploration. To maximize the number of initial concepts considered for each mission, mind maps (Pahl et al. 2007) were created for each transformation principle. This allowed early conceptual sketches of different system architecture to be organized by the transformation principle driving the greatest increase in mission capability.

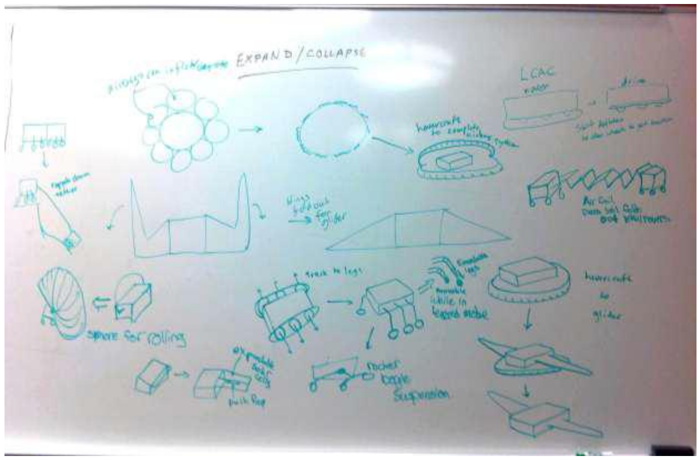


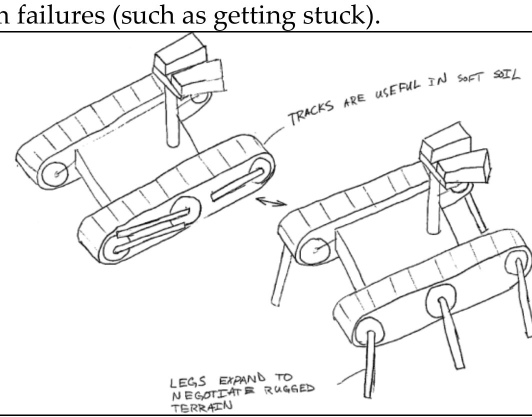
Figure 9. Conceptual sketches using the principle expand/collapse

The following four sub-sections introduce the concepts generated as part of this research effort. For each concept, the idea behind the design is explained, the primary transformation facilitator is identified (where possible), proposed advantages and disadvantages of the configuration change are introduced (highlighting the tradeoffs that a designer must make), and the system architecture ramifications are explored.

2.3.1 Expand / collapse

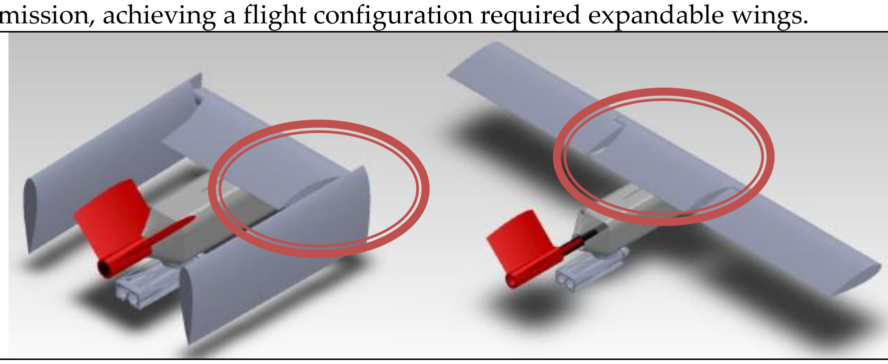
The concepts presented in this section leverage the transformation principle expand / collapse. As previously stated, this principle is defined by *changes in physical dimensions of an object along an axis, in a plan, or in three-dimensional space.*

Expand/collapse concept #1

Concept:	Deployable legs
Description:	A tracked rover than can expand legs from inside the tracks. The tracked mode would be the primary source of locomotion for most scenarios. Legs would assist in surmounting obstacles, navigating in rough terrain, or recovering from failures (such as getting stuck).
Depiction:	
Transformation facilitators:	<u>Shared power transmission</u> <u>Flip</u> <u>Furcation</u> **<u>Reorientation</u>**

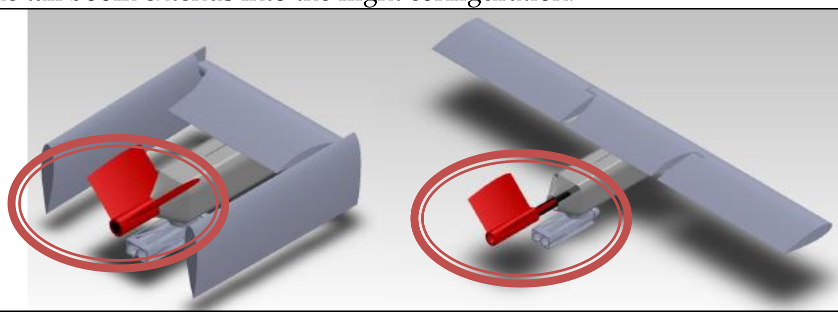
Advantages:	Tracks are good in flat ground and are particularly good on loose soil. The force spreads out over a larger area and the tracks deform the soil considerably less than a wheel. Furthermore, tracks are a relatively low energy choice in soft soil because the leading edge of the tread compresses the soil and the rest of the track moves over the firm compressed soil. Wheels have some spillage so subsequent wheels must do some of their own compressing. When the rover moves into rugged terrain, the legs would be used in a walking locomotion to increase the clearance under the rover so it can walk over rocks. The legs could also be actuated to help push the rover when motion by track locomotion is not adequate.
Disadvantages:	Sophisticated walking locomotion is not a fully matured technology. A rover could do shuffling quasi-walking which wastes a lot of energy. To do more natural walking gates, very sophisticated controllers are required.
Architecture ramifications:	The system must save space to stow the legs when not in use and must provide some mechanism for shifting the mechanical energy transmission from the tracks to the legs. For the rest of the architecture, the impacts are minimal.

Expand/collapse concept #2

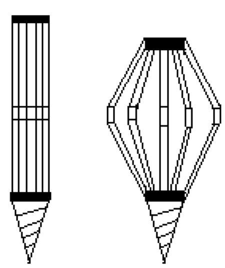
Concept:	Deployable glider wings
Description:	Packaging a glider would require space-savings for the journey to Mars and during terrain exploration. Designed specifically for the Melas Chasma mission, achieving a flight configuration required expandable wings.
Depiction:	
Transformation facilitators:	Conform with structural interfaces; Flip Furcation **Reorientation**
Advantages:	The wings are not in a lifting position during transit across the dunes. They are in a configuration that helps protect them during this phase. A spherical linkage accomplishes the complex three dimensional motion using only one actuator which reduces the number of points of failure for the transformation. The glider fits into its allotted space in a rover that is small enough to fit in the entry descent and landing capsule appropriate for the mission.
Disadvantages:	Segmented wings are weaker than continuous wings. An additional component must be moved into place to support the wing load because the spherical linkage is not strong enough for flight loading.

Architecture ramifications:	As the wings are one of the primary components of the glider architecture, this concept has moderate implications for the architecture. The volume the wings occupy is not consistently oriented so its use is limited to components that can be shifted around. There are implications for the other subsystems as well. The payload volume required of the mother rover is directly influenced by the packaging volume of the glider.

Expand/collapse concept #3

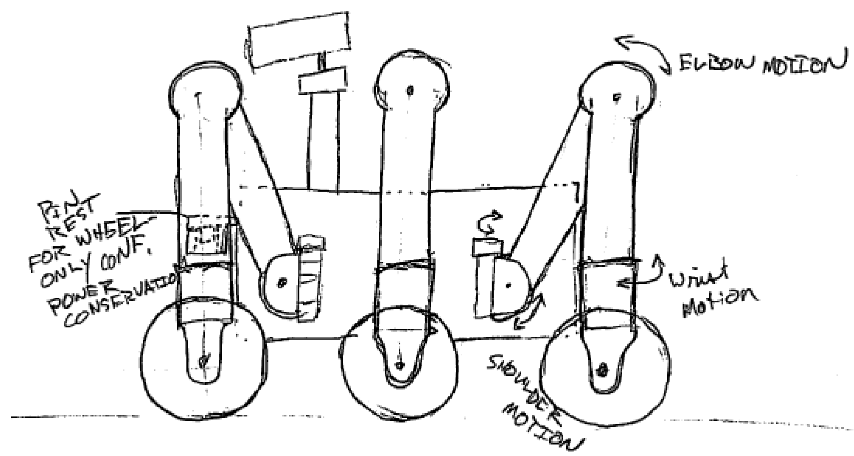
Concept:	Deployable glider tail
Description:	This concept is for the tail section of the glider. The tail boom compresses so the tail can be stored closer to the glider. When the glider is ready to deploy the tail boom extends into the flight configuration.
Depiction:	
Transformation facilitators:	Nesting
Advantages:	The glider fits in an acceptable storage volume until the flight phase of the mission.
Disadvantages:	The tail boom volume is not useful for other purposes.
Architecture ramifications:	Limited, as it is isolated to the tail boom component.

Expand/collapse concept #4

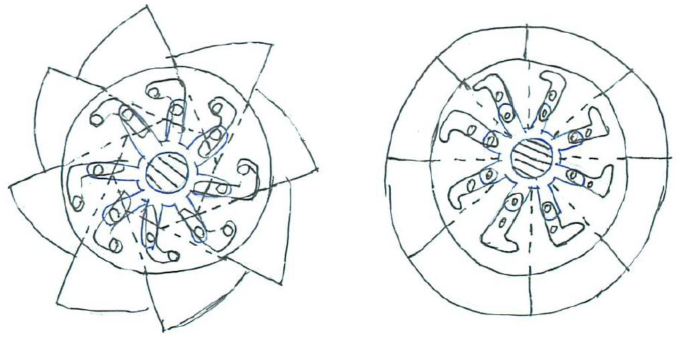
Concept:	Drill anchors
Description:	A concept where a foot consists of a drill that transformed into an anchor. In the collapsed state, it can drill a hole into the rocky surface. Once the hole is deep enough it can expand into an anchor to hold the rover on the NEO even if apparent local gravity is minute or negative.
Depiction:	
Transformation facilitators:	Function sharing
Advantages:	One component fulfills both the function of creating the hole and anchoring the rover in the hole.
Disadvantages:	The anchoring components may not be ideal to the task of transmitting the drilling loads. This could lead to over design of the shared component. A

	rover that drills a hole for every step would cover ground very slowly. Furthermore, the act of drilling may be disruptive to some of the scientific goal of observing and exploring the asteroid.
Architecture ramifications:	This concept requires that the rover architecture be a walking type since it is fundamentally a concept for a foot. It does not work on a rolling type rover. Otherwise, it does not impact the non-mobility systems to a very high degree.

Expand/collapse concept #5

Concept:	Walker-roller hybrid architecture
Description:	In this concept, a rover reconfigures from a walking mode to a rolling mode by expanding its legs to pick up its body. In the roller mode, the legs collapse down to rest on stops so that the energy is not needed in the leg positioning actuators to maintain the rover's posture.
Depiction:	
Transformation facilitators:	<u>Interchangeable transmissions</u>
Advantages:	Walking is a highly maneuverable locomotive form. It can enable higher ground clearance, better ability to navigate treacherous terrain, and the possibility to recover from failures by progressively freeing stuck legs. The rolling mode allows the rover to move on benign terrain in an energy efficient manner. The wheels and the legs could be used together in an active suspension rolling mode to create additional abilities.
Disadvantages:	Walking is a complex locomotive strategy requiring considerable sophistication of controller design.
Architecture ramifications:	This concept does not significantly impact any aspect of the rover architecture beyond the mobility subsystem.

Expand/collapse concept #6

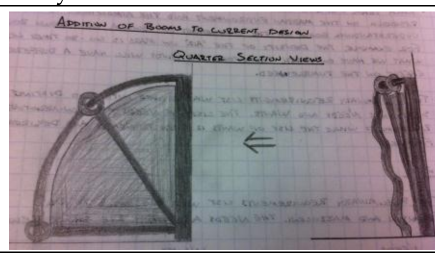
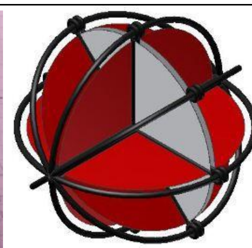
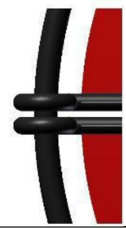
Concept:	Wedge wheel
Description:	In this concept, a wheel is made of several wedges that can be expanded into a pinwheel configuration.
Depiction:	
Transformation facilitators:	Segmentation
Advantages:	In the pinwheel formation, the wheel has additional surface area which will help it float in loose terrain. The points of the pinwheel will also act like cleats generating more traction in soft terrain and perhaps allowing it to move forward in soil that would bury a traditional wheel.
Disadvantages:	The mechanism to make the reconfiguration is necessarily complex as putting actuators in a wheel is a challenging design prospect. This complexity adds vulnerability that would need a mitigation strategy.
Architecture ramifications:	This concept does not significantly impact any aspect of the rover architecture beyond the mobility subsystem.

Expand/collapse concept #7

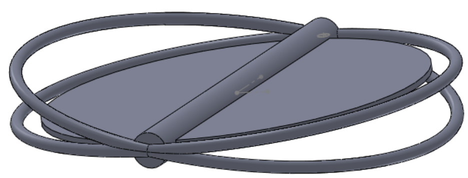
Concept:	Sails
Description:	The rover would have fabric sails that would be expanded when motion was desired, i.e. they would catch the wind when extended, or retract when the rover needed to stop.
Depiction:	
Transformation facilitators:	Material flexibility Structural constraint
Advantages:	This reconfiguration would give the rover the ability to start and stop and thus greatly increase the potential for scientific data collection during the course of the mission. The sails could also provide some control over rover

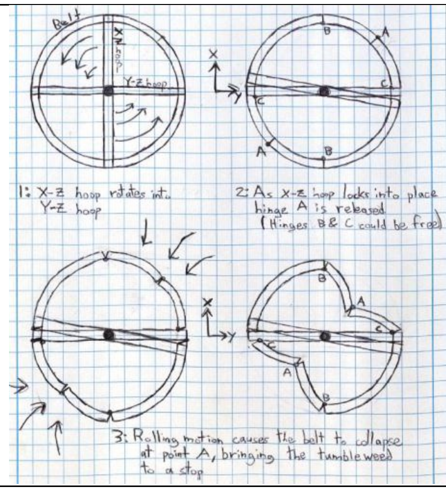
	travel speed and direction of travel by deploying only certain combinations of the sails.
Disadvantages:	The design to be used here could not be a fully covered system since the sails would clearly be ineffective in that case.
Architecture ramifications:	This system would not be difficult to incorporate into any of several possible designs for a tumbleweed rover. The main integration issue would be use of physical space for the control system and power allotment for the same.

Expand/collapse concept #8

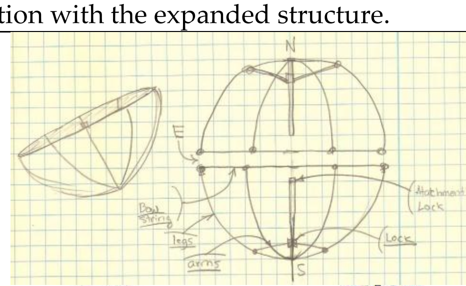
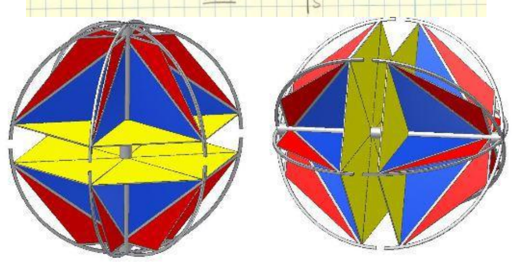
Concept:	Retractable boom deployment
Description:	The rover would be fully collapsed during the transportation phase of the mission and would have booms that expand the rover into its open mode on delivery.
Depiction:	  
Transformation facilitators:	<u>Material flexibility</u> <u>Function sharing</u> **<u>Expose / cover</u>**
Advantages:	This reconfiguration would allow the rover to be stowed in an extremely compact form relative to its expanded size. This allows a single mission to deploy a large number of rovers thus increasing the amount scope of data collection for the mission.
Disadvantages:	Design is constrained by disallowing any type of fully covered rover since the booms would have to fully surround the hoops.
Architecture ramifications:	Implementation of the system has fairly major design implications. The main hoops of the rover have to be flexible in one state and rigid in another. Inflatable structures are one possibility for allowing this, rigidizing through use of an epoxy applied as the boom extends is another.

Expand/collapse concept #9

Concept:	Folding hoops
Description:	Hoops that provide support for the rover pivot about the central mast to allow the rover to fold in half. Can also include an additional 'belt' for added support at the cost of a more complicated folding motion.
Depiction:	

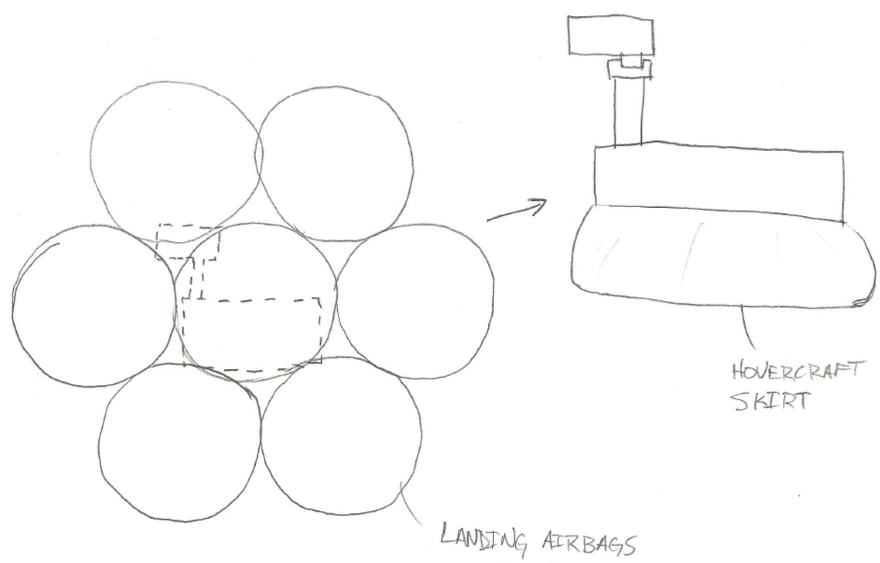
	
Transformation facilitators:	<u>Nesting</u>
Advantages:	Allows for a drastic reduction in packed size. This system could also be used to cause the rover to stop, as with the sails, in order to accomplish more detailed science goals.
Disadvantages:	Difficulty of achieving system deployment.
Architecture ramifications:	This concept places fairly heavy design constraints on the rover geometry. It could possibly be used in a solid skinned tumbleweed design but is more likely to be another open rover solution. This system also constrains design for secondary components to being flat in one dimension to allow them to comply with the flattened geometry.

Expand/collapse concept #10

Concept:	Umbrella deployment
Description:	The two halves of the rover would be able to expand and retract in a manner analogous to an umbrella. This design would also incorporate sails that deploy in conjunction with the expanded structure.
Depiction:	 
Transformation facilitators:	<u>Material flexibility</u> <u>Furcation</u> <u>Segmentation</u>

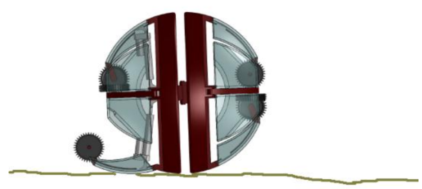
Advantages:	Directional control could be achieved by adding additional stable points between fully expanded and fully collapsed, changing both the physical geometry as well as the amount of sail exposed to the wind. This would also allow the rover to be stopped, a major advantaged to any tumbleweed design. It also has a very compact storage state.
Disadvantages:	Multiple support pieces must be designed and controlled using an actuation scheme. This requires power and could introduce sources of failure.
Architecture ramifications:	This again imposes major architecture constraints and could not be easily integrated into another rover design. The rover would essentially have to be custom designed to operate in this manner. It could have other systems that integrate into it, however, e.g. since the supports are already designed to be flexible, the actuated deformation could be incorporated and the retractable sail system could also be added on.

Expand/collapse concept #11

Concept:	Landing bags as hovercraft skirt
Description:	This concept involves repurposing a landing airbag system to function as a skirt to allow the vehicle to function as a hovercraft. Once the vehicle had come to a stop, the airbags would be deflated and caused to hang around the edges of the rover.
Depiction:	
Transformation facilitators:	<u>Material flexibility</u> <u>Function sharing</u> <u>Enclosure</u> **<u>Reorientation</u>**
Advantages:	This design would be offer the advantage of making extended use of the considerable weight of the airbag landing system. It would also have the ability to glide over small obstacles and very loose sand.
Disadvantages:	Limited in terms of ability to navigate larger rock fields.

Architecture ramifications:	This system would largely impact the entire architecture of the mission and would consequently have to be designed for from the start rather than integrated. A ground craft without wheels has not been used before for planetary exploration, so it would require extensive testing and development as well. Finding a way to reconfigure the airbags such that they make a continuous skirt would likely also impact the possible configurations available for the airbag design.

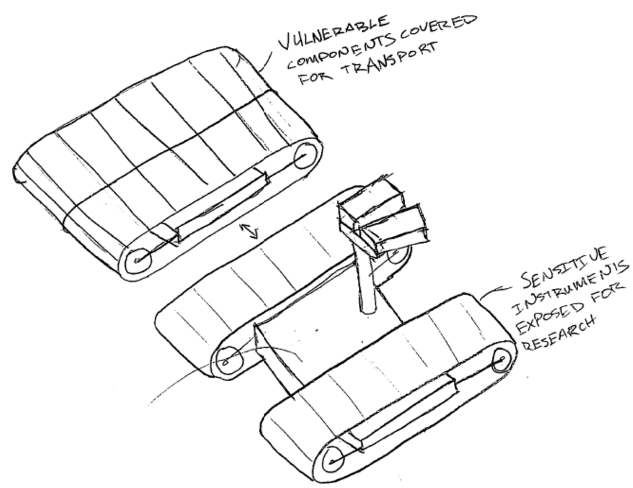
Expand/collapse concept #12

Concept:	Enable rolling
Description:	For spherical systems, a quarter-leg could be extended to provide initial motion.
Depiction:	
Transformation facilitators:	<u>Conform with structural interfaces</u> <u>Enclosure</u> <u>Flip</u> <u>Furcation</u> <u>Segmentation</u>
Advantages:	The purpose of this transformation is two-fold. When at the top of a cliff, the extension of a quarter-leg could provide the necessary shift in center of gravity to allow rolling to begin. Additionally, this transformation could be used to provide a degree of steering.
Disadvantages:	Significant actuation concerns. Power requirements are not trivial. Control scheme must be intelligent enough to properly control movement.
Architecture ramifications:	Transformation is an essential element of the rover architecture. Packing, controls, and power concerns must all be taken into consideration. The way the legs are hinged force the wheels to collapse into crowded spaces on the poles of the sphere.

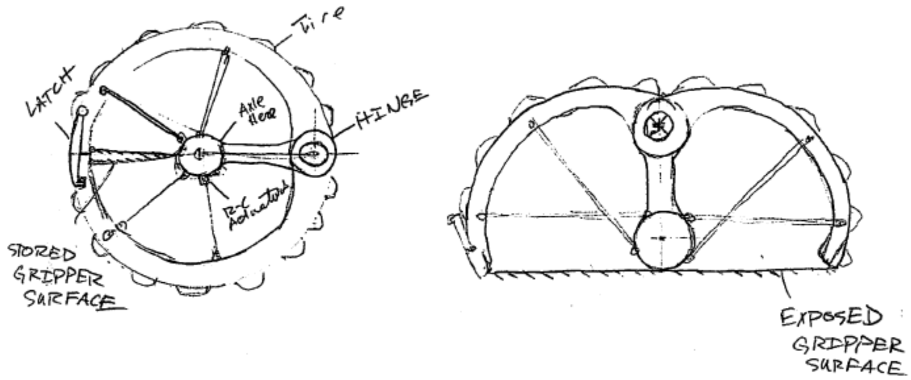
2.3.2 Expose / cover

The concepts presented in this section leverage the transformation principle expose / cover. As previously stated, this principle is defined by *exposing / covering a new surface to alter system functionality.*

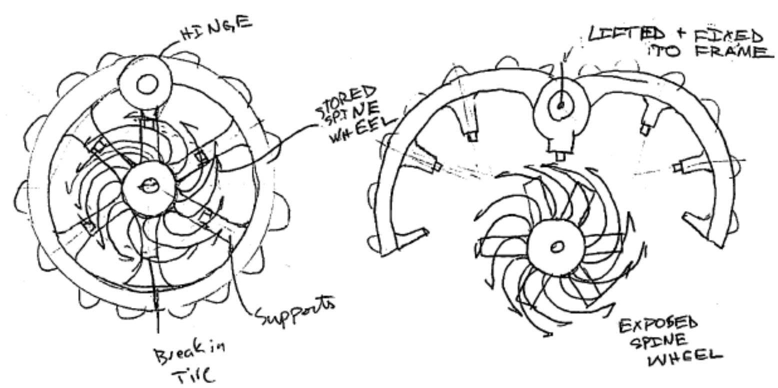
Expose/cover concept #1

Concept:	Tracks protecting rover
Description:	In this concept, the tracks of a rover cover the sensitive portions of the rover during transit for protection. When the rover reaches a destination of scientific significance, the sensors are exposed for exploration.
Depiction:	
Transformation facilitators:	<u>Enclosure</u> <u>Furcation</u> <u>Nesting</u> <u>Shelling</u> **<u>Expand / collapse</u>**
Advantages:	In this collapsed mode, this rover might be able to travel at higher speeds over rougher terrain than a traditional rover because the sensitive equipment is protected from the terrain. Impacts to the tracks would transmit smaller forces to the fragile equipment allowing a more aggressive mobility for this rover.
Disadvantages:	Some instrumentation must be used for navigation during the transit phase. This strategy would have to be implemented carefully to avoid losing the entire advantage due to the exposed instruments.
Architecture ramifications:	This concept has significant impacts to the system architecture as the sensor suite must obey the constraint of having to fit between the treads in the travel mode.

Expose/cover concept #2

Concept:	Spine foot
Description:	This concept is a wheel that opens like a clamshell to expose a microspine surface for climbing.
Depiction:	
Transformation facilitators:	<u>Material flexibility</u>
Advantages:	In the foot configuration, the microspine surface is very useful for connecting to hard, rough rocky surfaces. This could be useful for a climbing rover to ascend a mountain or descend a canyon with a rocky wall. The wheel configuration would be for low energy travel over benign terrain.
Disadvantages:	The foot configuration cannot share the rolling locomotion of the wheel. Therefore the rover would need a walking locomotion mode to leverage the microspine feet. Also, some strategy for protecting the transformation mechanisms from dirt, dust, and debris would be needed to prevent degradation over the course of the mission.
Architecture ramifications:	The architecture impacts for this concept are rather involved as the rover would need two locomotive modes. It would have to have a configuration for rolling movement when the wheel is closed. The opened wheels do not roll so the rover would need to be able to do walking movement in order to be able to use the feet.

Expose/cover concept #3

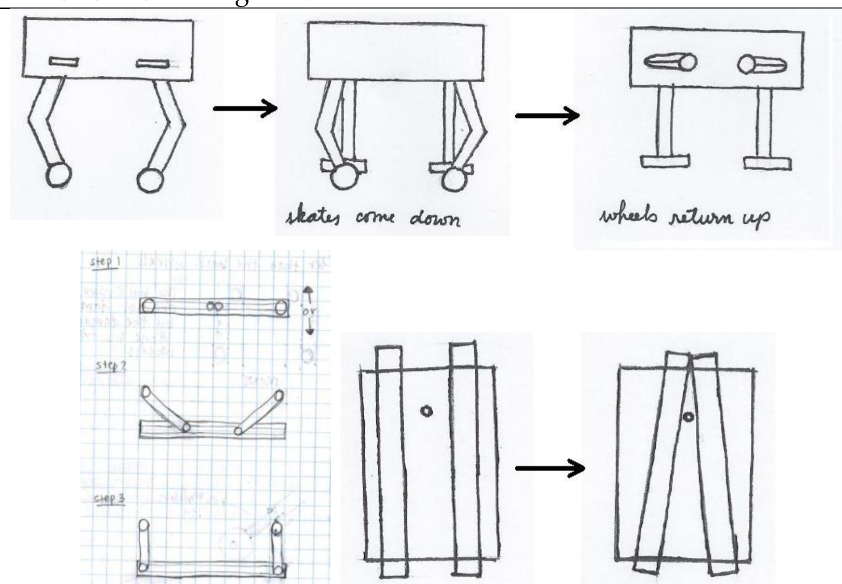
Concept:	Spine wheel
Description:	In this concept a spine wheel is nested inside a more traditional rover wheel. The traditional wheel can be opened and stowed to expose the spine wheel.
Depiction:	

Transformation facilitators:	<u>Nesting</u>
Advantages:	The spine wheel is superior for traction on rocky surfaces. A climbing locomotion could be accomplished using this spine wheel. The traditional wheel is for non-climbing locomotion. It would have considerable advantage in durability and should require considerably less energy to use than the spine wheel. Thus, this concept would allow a rover to roll to a cliff, expose its spine wheels, and climb the cliff. Unlike the spine foot, this concept utilizes the same energy transmission in both modes which simplifies its architecture implications.
Disadvantages:	Spine wheels are not understood as well as microspine feet. The wheels must be stowed in such a way that they do not interfere with the operation of the rover.
Architecture ramifications:	The only additional architecture impact is that some strategy for stowing the wheel must be included. Otherwise, these wheels could be traded into any rover architecture although the effectiveness of a climbing rover may depend on other architecture implications such as the height of the center of gravity.

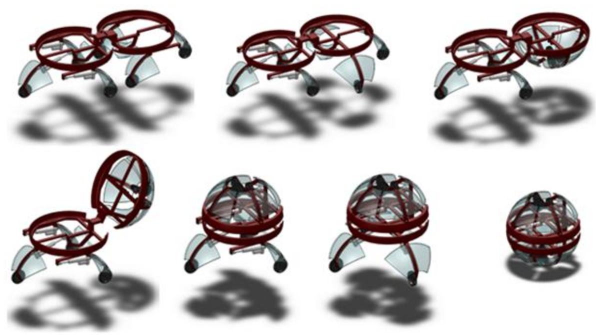
Expose/cover concept #4

Concept:	Aerial explorer deployed from a ballistic shell
Description:	In this concept, a ballistic shell containing an Unmanned Aerial Explorer is launched from a compressed air cannon. The Aerial Explorer is deployed from the ballistic shell using an expose transformation.
Depiction:	
Transformation facilitators:	<u>Shelling</u>
Advantages:	The ballistic shell protects the aerial explorer during its launch and early flight phase. It delivers the airplane to a speed and altitude at which lifting flight can safely begin. In ballistic shell mode, the vehicle can capitalize on Mars's low atmospheric density to gain altitude and speed. In flight vehicle mode, the system can maintain its altitude for wide area exploration.
Disadvantages:	The detailed design of the transformation from ballistic mode to flight mode is critical so the energy of the cannon is not lost to drag when the system transforms.
Architecture ramifications:	The architecture of both the ballistic shell and the aerial vehicle are highly constrained by the need for mutual compatibility.

Expose/cover concept #5

Concept:	Wheel/skate or ski
Description:	This rover could alternate between locomotion via wheels or skates by alternately raising separate appendages. It would have two independent sets of supports that would be raised or lowered depending on prevailing conditions (i.e. firm ground or ice). Another variation on this design would use skis instead of skates as the alternate mode of travel since they could be easier to control during a descent.
Depiction:	
Transformation facilitators:	<u>Common core structure</u> <u>Shelling</u>
Advantages:	Ability to move efficiently in separate types of terrain.
Disadvantages:	A change in terrain characteristics can render the rover much less useful or even strand it entirely as happened with Spirit.
Architecture ramifications:	Added mass and complexity of deploying various means of ground contact.

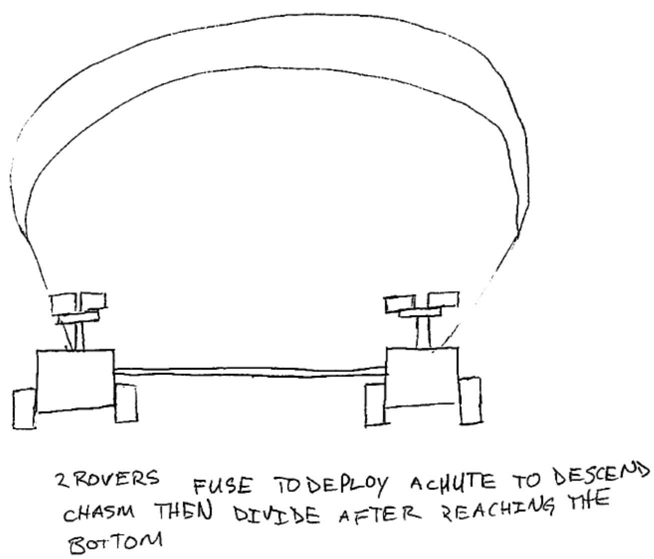
Expose/cover concept #6

Concept:	Roving-rolling
Description:	Motivation is to combine a traditional wheeled architecture with a rolling mode of locomotion. This system has 6 wheeled legs in the roving mode but 8 quarters in the rolling mode. The spherical configuration has two circular halves, each with 4 quarters. The transformation is achieved by a rotary motion of the legs hinged about the chassis, to collapse into a hemisphere in each half. Then both halves collapse into a sphere.
Depiction:	
Transformation facilitators:	Segmentation Function sharing Flip **Expand / collapse**
Advantages:	The primary advantage is that it enables a rover to navigate flat and moderately rugged terrain while rolling. For steep slopes, the system can transform into a sphere. Wheeled rovers are limited by the traction they can generate on a given slope and the maximum tilt they can withstand before overturning. Re-configurability allows this system to overcome such limitations by transforming into a rolling mode.
Disadvantages:	To preserve the dynamic advantage of a sphere in free rolling it is critical that the center of mass of the sphere be at the center of the sphere. In addition to the existing space constraints, this forces constraints on the placement of various objects based on their weight and thus forces an overall symmetric placement of actuators, payload, communication and power.
Architecture ramifications:	Transformations must be designed in a way such that parts do not physically overlap or interfere with each other. All components must be placed within the spherical enclosure.

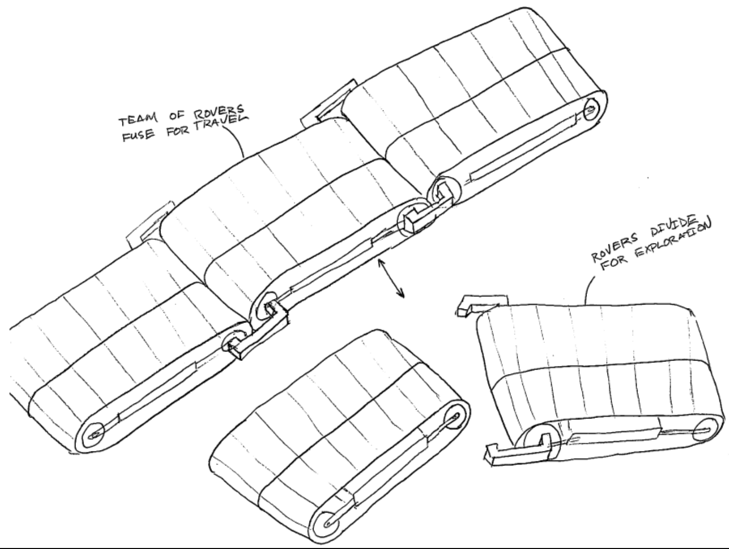
2.3.3 Fuse / divide

The concepts presented in this section leverage the transformation principle fuse / divide. As previously stated, this principle is defined by *making a single functional device become two or more devices, at least one of which has its own distinct functionality defined by the state of the transformer or vice versa.*

Fuse/divide concept #1

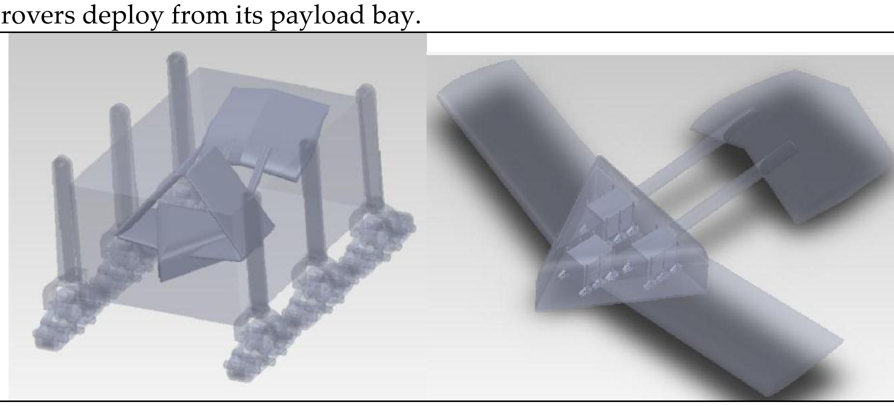
Concept:	Parafoil
Description:	This concept is for two (or more rovers) to fuse together and for the purpose of deploying a parachute or parafoil to descend to the bottom of a chasm. As conceived during this project, the two rovers would be located at either end of the parachute.
Depiction:	
Transformation facilitators:	Function sharing Modularity Composite Segmentation
Advantages:	Capable of slowing rate of descent if vehicles are in free-fall from a large height.
Disadvantages:	A list of problems exists for this idea. It is not any better than providing a smaller chute for each rover. The large low density of Martian air requires that any flying be done with a large planform area and/or at very high speeds. A large planform parafoil is highly susceptible to turbulence as segments of it could be subject to different local wind than the rest causing collapse of the parafoil due to the strains created. Relying on high speed flight exacerbates design for safe take-off and landing. Finally, this concept compounds the risk to the mission as a failure during flight means both rovers crash and are lost instead of just one.
Architecture ramifications:	The overall impact would be minimal. The rovers need a way to connect to the chute and a way to avoid crashing into each other in flight such as a spreader. However, providing individual chutes for each rover would have a smaller impact as the spreader would be unnecessary.

Fuse/divide concept #2

Concept:	Combined rover concept
Description:	For this concept, several rovers would be produced such that they have an interface for connecting together into one larger vehicle.
Depiction:	
Transformation facilitators:	<u>Common interface</u> <u>Modularity</u> <u>Composite</u> <u>Segmentation</u>
Advantages:	The combined rover would be advantageous for the travel phases of the mission. It could be designed such that it is more capable in chaotic terrain. That is, a vehicle consisting of three six-wheeled vehicles would have eighteen wheels and could survive much more easily if one or two went into loose soil. If there was some way to actuate the position of one rover with respect to the others, the large rover may have the ability to climb over larger obstacles than the individual rovers by lifting one rover onto an obstacle which could in turn pull the other rovers up onto the obstacle with it. There may be some energy savings associated with moving as one unit or only running one navigation computer with the other rovers slaved to the master controller. There may be some mass saving available by having only one communication antennae. When the rovers reach a location of scientific interest, they would divide and perform their assigned tasks. Multiple rovers could explore an area more quickly than one big rover. Having the capability to divide into smaller fully-functional rovers mitigates mission risk. If one part of a traditional rover breaks, it can severely degrade system performance or end the mission entirely. However, if the system were designed to be dividable, the remaining functional rovers could continue the mission with full functionality. Finally, multiple rovers create the possible risk mitigation strategy of rescue. That is, if one rover gets stuck, the others may have the capability of helping it get unstuck.

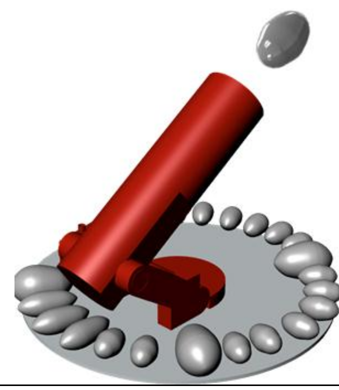
Disadvantages:	Less available payload for each individual rover means each small rover would have less scientific ability than one large rover of similar system mass. This disadvantage could be mitigated somewhat by distributing different sensors to different individual rovers although, that would have to be traded against the effectiveness of the risk mitigation proposed in the advantages.
Architecture ramifications:	The impacts on the architecture decisions could be kept relatively minor or could be much larger depending on how much additional functionality is designed into the combined rover. That is, if the large rover is just a train of smaller rovers moving together the only architecture impact is the connection component needs to be included. If more capability, such as lifting rovers up over obstacles, is desired from the combined rover, the architecture impacts increase as the actuations have to be accounted for as well.

Fuse/divide concept #3

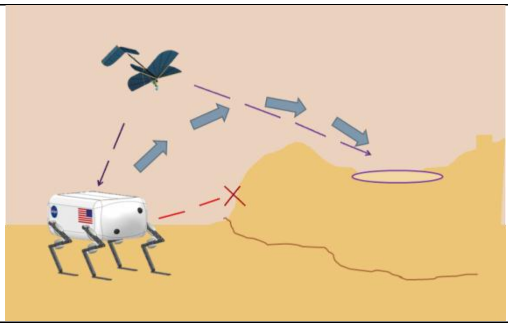
Concept:	Carrier rover
Description:	In this concept a "mother ship" vehicle carries another vehicle to some destination where the "child vehicle" can deploy. This concept manifested itself in two ways for the glider mission into Melas Chasma. A dune-crossing rover carries a glider to the edge of chasm where it launches and descends into the canyon. Once the glider lands at the bottom, three micro rovers deploy from its payload bay.
Depiction:	
Transformation facilitators:	Nesting Shelling **Expand / collapse**
Advantages:	This concept enables a mission into a previously un-explored region of Mars. It is a way to leverage the design concept of modularity for a complex system. There are some functionality that is only needed part way through the mission such as the ability to cross sand dunes. Dividing the system allows the components and associated mass that provide that function to be left behind. In the case of the glider, this enables the flight into the chasma which would be considerably more difficult if the glider had to carry its mother ship with it. Again, at the bottom of the canyon, the glider's functionality is no longer needed so it, too, can be discarded from the system which goes on to do its exploration.

	Careful design of the various components may allow them to add additional value to the mission after their primary purpose is fulfilled. For example, the mother ship could follow the mini rovers along the rim of the chasma and serve as a communication link to orbit and/or back to Earth.
Disadvantages:	Using this concept, large amounts of system mass get discarded over the course of the mission. This is mass that cannot be embodied as sensors. As such, this is a strategy best used for very difficult tasks such as going to new places. It probably is not a good strategy for rolling around the rock fields that are easier to reach.
Architecture ramifications:	This concept is an architecture-level concept. As such, it affects most aspects of the architecture decisions. The entire system must be designed with the various packaging implications in mind.

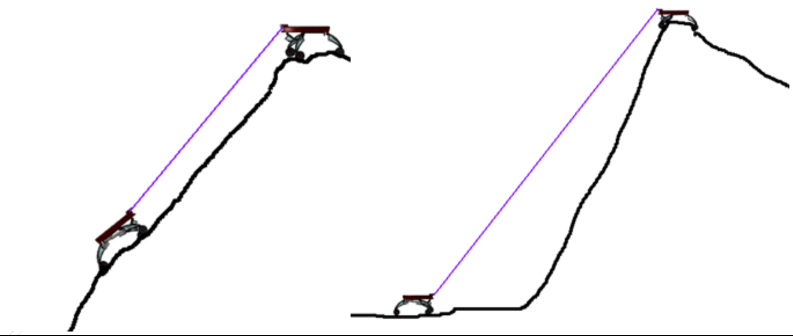
Fuse/divide concept #4

Concept:	Ballistic launch of an aerial explorer
Description:	In this concept, a compressed air cannon fires a projectile shell carrying an Unmanned Aerial Explorer. The shell divides from the cannon to start the mission.
Depiction:	
Transformation facilitators:	<u>Nesting</u>
Advantages:	Low atmospheric density on Mars means high speeds and/or large wings are required in order to create sufficient lift for flight. This is most critical for take-off and landing phases where the ground is close and large accelerations are needed to move from the at rest position to flight velocity or vice-versa. However, the low density also means drag is very low on Mars which makes ballistic motions considerably more efficient. The air cannon concept leverages this to solve the take-off problem for Martian flight. The main energy source and associated mass is left on the ground by the divide principle which makes the required size of the explorer manageable.
Disadvantages:	A localized take-off infrastructure makes the prospects of re-using the airplanes very low.
Architecture ramifications:	This concept has considerable architecture implications as components of the ground station must be sized in response to properties of the ballistic shell and components of the aerial vehicles must be designed to sufficiently bear the loading of the launch.

Fuse/divide concept #5

Concept:	Flying scout
Description:	This concept involves a main rover carrying one or more small flying scouts. These scouts survey the rover's immediate area in all directions to provide data on the most efficient path for movement. The most suitable architecture for the scout would be a small entomopter with flight characteristics much like a dragonfly.
Depiction:	
Transformation facilitators:	<u>Nesting</u> <u>Shared power transmission</u> <u>Common core structure</u> <u>Modularity</u>
Advantages:	The insect-like aerodynamics lend themselves to the low Reynolds number regime prevalent on Mars due to the low atmospheric density. This concept could aid in locating scientific objectives near the rover's path that it might ordinarily pass by. It would also aid in route selection by giving the rover extended information on the surrounding terrain.
Disadvantages:	Insect flight is not well understood, even on Earth, so this would also require significant cost in terms of development of the technology.
Architecture ramifications:	This could potentially be incorporated into any rover design without major changes to the overall architecture. The main integration issue would be physical space to store the scout; preliminary estimates on entomopter size indicate that its wingspan would need to be on the order of a meter. Other integration issues would include the significant increase in power required for charging the scout as well as the addition of computational resources to control the entomopter flight.

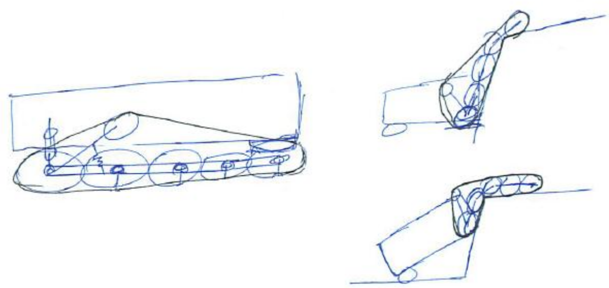
Fuse/divide concept #6

Concept:	Crater exploration concept
Description:	Divide the main chassis into two halves that can physically separate from each other while remaining connected by a tether. Once half of the system reaches the crater base, it is able to rove and explore. It could also pick up samples for later analysis in the instrumentation potentially located on the anchored half. Once the exploration is complete, the anchored half winches the exploring half back up and they relock.
Depiction:	
Transformation facilitators:	<u>Segmentation</u> <u>Generic connections</u> <u>Function sharing</u> <u>Conform with structural interfaces</u> <u>Modularity</u>
Advantages:	Impact Craters are of prime scientific interest on planetary bodies, and exploring their bases would grant access to invaluable data. Because of the steep slopes along the crater walls a traditional wheeled rover would not be capable of exploring it. Even if it can conquer the slopes on the outside and reach the rim avoiding the risk of overturning, the insides of craters usually present steeper more challenging terrain.
Disadvantages:	A significant variety of complexities and challenges arise with this concept. Knowledge of soil and terrain at crater rim might be needed to develop a proper anchoring system.
Architecture ramifications:	Overall the design of the two halves should be such that they are self-sufficient in terms of basic needs like energy, brains and communication. There should be independent power sources for the two halves, with a processor and transceiver on each. For other resources like sensors and instruments, a detailed analysis should determine efficient resource sharing and splitting strategies. For example data from certain sensors on one half can be used in decisions made by the processor on the other half. Instruments on the two halves should be places such that the instruments that need to take in-situ measurements are on the exploring half and instruments like a spectrometer can be located on the anchored half to which samples can be brought back to for later analysis. The most obvious challenge is the design of the joint between the two halves of the rover. The actuation for the winch, locking mechanism and the articulation of the hip joint all demand different types of actuators but have to fit into a tight volume constraint

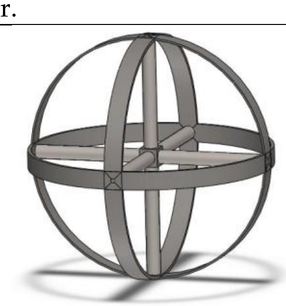
2.3.4 Reorientation

The concepts presented in this section leverage the transformation principle fuse / divide. As previously stated, this principle is defined by *creating a new system configuration by reorienting an aspect of the system in a new way*

Reorientation concept #1

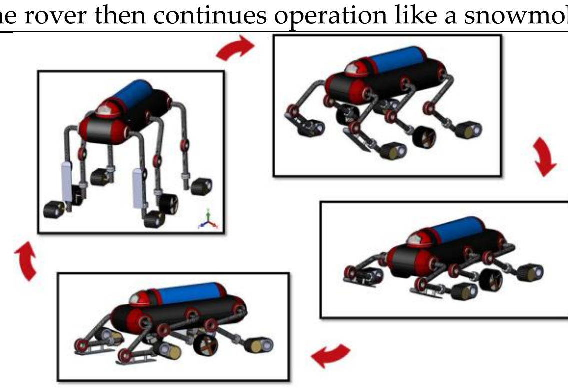
Concept:	5-bar robot tracks
Description:	In this concept, the tracks are configured as a planar robotic arm. The arm can be reconfigured into many different shapes to enable a wide variety of maneuver capabilities.
Depiction:	
Transformation facilitators:	<u>Material flexibility</u>
Advantages:	The flexibility provided by these tracks allows the ability to overcome a wide variety of obstacles. The rover can raise itself up to drive over high rocks. It could do this on one side only in order to maintain its balance when travelling cross-wise along an incline. It can climb small cliffs by placing the tips of its tracks atop the obstacle and progressively moving wheels up and over the cliff.
Disadvantages:	The complex motion of this system requires sophisticated control and decision making to leverage its full potential. Many components in the tread likely add up to considerable extra mass.
Architecture ramifications:	This concept does not significantly impact any aspect of the rover architecture beyond the mobility subsystem.

Reorientation concept #2

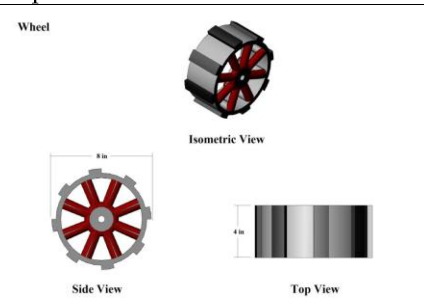
Concept:	Physical deformation of sphere
Description:	Here the rover's exterior supports would be designed to be flexible enough to be deformed by actuation, i.e. the rover would have interior actuators that stressed the supports causing them to bend and thus change the rolling characteristics of the rover.
Depiction:	

Transformation facilitators:	Conform with structural interfaces Material flexibility **Expand / collapse**
Advantages:	The potential advantages to this system include the ability to get some control over rolling direction and aid in stopping the rover, although considerable deformation would likely be required for this system to stop the rover entirely by itself.
Disadvantages:	Actuation control could be difficult. Understanding material properties to deform without significant stress / strains could require significant effort.
Architecture ramifications:	Significant. The architecture is defined by the transformation.

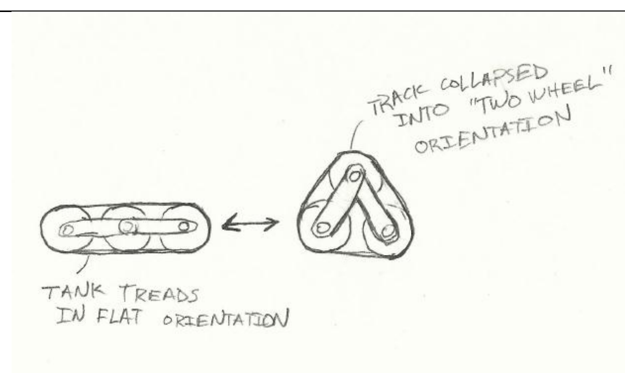
Reorientation concept #3

Concept:	Track/Wheel/Ski
Description:	This rover uses six legs with tracks on the fore and aft and wheels on the middle set of legs. When the rover encounters snow or ice, the legs are folded in and skis on the upper section of the front legs are used instead of the tracks. The rover then continues operation like a snowmobile.
Depiction:	
Transformation facilitators:	Flip Common core structure **Expand / collapse**
Advantages:	The advantage provided in this concept is the ability to move efficiently in two separate types of terrain. This is one of the main advantages that reconfigurability can convey to a system. As missions are broadened and expected to travel greater distances, the widely varying Martian terrain types will begin to have a larger impact on rover design. Systems that can change their function depending on the current conditions will offer greater overall performance.
Disadvantages:	Ski design needs to be verified for use on Martian surface. Actuation could require significant power.
Architecture ramifications:	This design constrains the architecture of any rover it is used on considerably. The main body needs to be long to allow the legs room to have their full range of motion. The suspension is heavily constrained as well to be specifically designed to incorporate the reorientation, e.g. the legs must be fully articulating to allow the skis to be engaged. This represents reconfigurability that is designed in from the start rather than incorporated into an existing system.

Reorientation concept #4

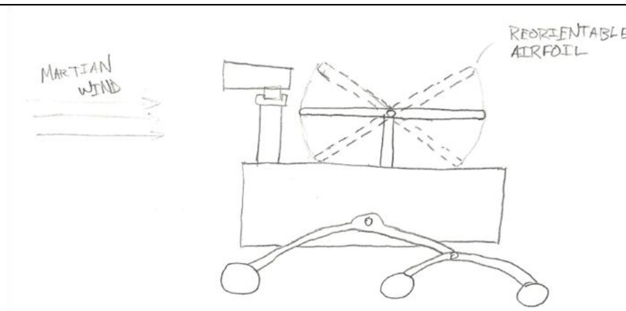
Concept:	Wheel acting as windmill
Description:	This concept would use the spokes of a wheel on the rover as vanes for a windmill to provide an extra boost of power for the rover. The wheel would be lifted off the ground and extended up into the air where the airfoil shaped spokes would generate power as the wind turns them.
Depiction:	
Transformation facilitators:	Function sharing Shared power transmission
Advantages:	The advantage to this would be that the rover is essentially getting an extra power source for relatively little cost. The wheel is already necessary for the rover's locomotion and repurposing it during periods when the rover is not moving would allow it to extend its functionality.
Disadvantages:	Not explored.
Architecture ramifications:	This system could be integrated into any wheeled design that has the capability to raise a part of its suspension off the ground. It would not require any drastic changes to the architecture of the wheel or rover. Since relatively few designs have a suspension that allows a wheel to be raised, however, that requirement does present a significant hurdle to implementation.

Reorientation concept #5

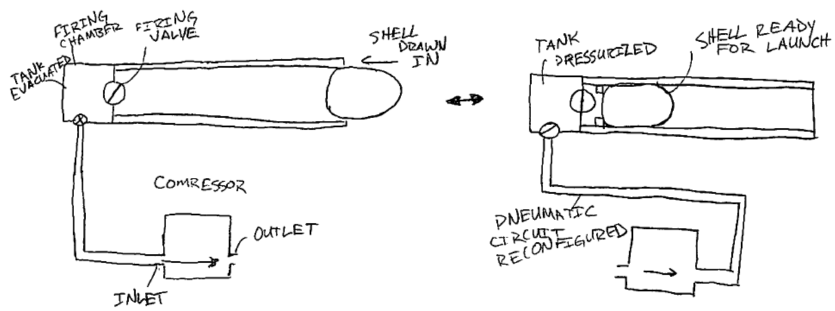
Concept:	Reorienting treads
Description:	This concept uses a three wheeled tread that can be folded such that either two or three of the wheels are engaged to put the tread in contact with the ground.
Depiction:	
Transformation facilitators:	Material flexibility Segmentation

	Expand / collapse
Advantages:	The advantage to this design would be the ability to change the weight distribution on the treads as well as their length. This could be useful since the collapsed tread could be used when tight maneuvers are needed (such as in a rock field) and the fully extended tread could be used when traveling over soft soil to prevent sinking.
Disadvantages:	The extra motors and joints required to accomplish the folding of the tread suspension would represent a challenge in terms of space and weight. The most significant drawback to this system would be that incorporating complicated moving parts into the treads would necessarily impact their robustness, one of the main reasons treads have an advantage over wheels.
Architecture ramifications:	This system would not represent a major change in tread architecture and could be integrated into a variety of treaded rovers.

Reorientation concept #6

Concept:	Solar panel airfoil
Description:	This concept would involve mounting an airfoil on top of the vehicle that could be reoriented to provide varying degrees of vertical force on the rover as the Martian wind interacted with it. If the vehicle needed extra traction or was stuck and needed a slight lift, the airfoil angle of attack could be altered to provide either.
Depiction:	
Transformation facilitators:	<u>Function sharing</u> <u>Shared power transmission</u>
Advantages:	The advantage gained from this system would be that the rover could cope more easily with varying terrain conditions. The ability to alter the effective normal force supplied to the rover wheels could be of major assistance in situations such as the one Spirit was unable to recover from.
Disadvantages:	The most significant challenge to implementation would likely be rearranging scientific or functional instruments on the top of the rover to account for the fact that it would be under cover.
Architecture ramifications:	This would be a simple matter to integrate into almost any rover design.

Reorientation concept #7

Concept:	Repurposing a compressor for projectile loading
Description:	In the air cannon concept, the energy for launch is provided by a compressor in the ground station. The compressor's pneumatic circuitry can be reconfigured for use to assist loading the shells into the cannon. In one configuration the inlet side of the compressor is attached to the firing chamber to produce a vacuum that can help draw the shell down into firing position in the cannon. Then the vacuum is vented, the compressor is reconfigured so that the outlet side is connected to the firing chamber. The firing chamber is compressed in preparation to the launch of the shell.
Depiction:	
Transformation facilitators:	Shared power transmission
Advantages:	One subsystem provides the energy for both the loading and the firing functions of the system. No additional mechanisms are required to load the shell in the cannon.
Disadvantages:	The compressor specification will be constrained by the need to be able to provide a vacuum as well as a pressure.
Architecture ramifications:	This concept removes the necessity of an additional loading subsystem from the architecture and therefore has a positive influence on the system.

Before describing the final conceptual designs from the Phase 1 effort, it is prudent to discuss the higher-level conclusions drawn from the systematic study. The following section highlights major conclusions from our exploration of transformative reconfigurations in planetary space vehicles.

2.4 Lessons learned from systematic study of transformations

This section explores the high-level conclusions drawn by the research team after completing the systematic study in the previous section. At the end of each sub-section, a conclusion is offered that offers summarizing thoughts and highlights the thought process behind concept selection in Section 3.

2.4.1 Fuse/divide: Facilitated by segmentation and modularity

The transformation principle fuse/divide has seen many applications in the last 60 years of spacecraft development. 'Staging,' for example, is an application of the fuse/divide principle that was developed in response to the high speeds necessary to achieve orbit. By mounting two or more rocket systems in a linear sequence, launch vehicles jettison used stages and increase their acceleration by igniting the smaller, lower-thrust next stage to achieve a desired velocity.

Fuse/divide has also played a significant role in manned and unmanned missions. Perhaps most significantly, the Apollo missions provide an example of how this principle led to architecture transformations that enabled a mission otherwise thought impossible (Orloff and Harland 2006). Fuse/divide has also allowed the Solid Rocket Boosters and external fuel tank of the Space Shuttle to be continually reused. More recently, the Mars Science Laboratory (MSL) used fuse/divide in support of achieving a "soft-landing." A sky-crane was successfully used to slow the rover to a near-zero velocity on landing. The MSL was then lowered to the ground using a bridle and an "umbilical cord". When the MSL was safely situated on the surface, the sky-crane detached itself and used the remaining fuel to crash-land at a safe distance from the rover (Ivanov et al. 2011).

These instances of fuse/divide are facilitated by segmentation and modularity. The reliance on segmentation is not surprising, as it has been defined as "*dividing a single contiguous part into two or more parts*." While this explains the "divide" nature of the concepts, our study showed that a degree of modularity was necessary (or assumed necessary) to bring the concept to fruition. Modularity has been well researched for its ability to provide 'plug-and-play' capabilities, allowing components to be added or removed from the base architecture (Dahmus et al. 2001, Simpson et al. 2006, Gershenson et al. 2004, Martin and Ishii 2002). In this context, complex systems are comprised of components with localized functionality that can be added or removed from a system.

Designing complex systems out of plug-and-play modules is not always possible, nor practical. While consumer electronics lend themselves to modularity, complex systems like spacecraft have so many integrated aspects to consider that it makes the iPad's design seem like "basic arithmetic" (MacDuffie and Fujimoto 2010). What was also noticed, however, is that modularity was rarely used to design a single system. Rather, modularity was used to create systems comprised of identical, or nearly identical, individual systems that could be combined together to carry out a mission. From a literature perspective, this has been seen in the PolyBot design. However, a significant aspect of PolyBot is the relatively simple architecture that defines each module – inherently each individual module has a significantly reduced functionality.

The six fuse / divide concepts presented above tell a slightly different story. In three of the designs (Concepts 1, 2, and 6), the fuse / divide principle is used to joint two independent systems that have complex levels of functionality. A challenge of this designing this type of system is that each module must be independently capable – requiring power, navigation, control, etc. The design decision to be made here is whether the complexity of the design warrants the possible performance gain. For instance, in Concept 6 fuse / divide is used to segment the system into two modules, allowing the spacecraft to explore terrain that would not be possible if the system remained in its original configuration.

The remaining three concepts (Concepts 3, 4, and 5) use segmentation and modularity primarily to carry and deploy smaller vehicles from a larger "mother-ship" configuration. Here, the fuse / divide nature of the transformation is mainly due to the necessity of transportation and storage. While these concepts have interesting potential, it is unclear if they are truly a "transformative" modification of system architecture. Rather, the benefit may come in finding additional uses for the "mother-ship" system, such as acting as a communication or relay platform.

Conclusion: The principle of fuse/divide has a rich history in space exploration and is mainly facilitated by segmentation and modularity. Modularity has been extensively explored, especially at the sub-system level. When higher levels of system architecture are considered, the fuse/divide principle alone appears to have limited ability to revolutionize planetary rover design. Further, system-level segmentations often result in two fully independent systems that must be designed and evaluated. However, when this principle is linked with other principles (as in Concept 4 and 6's designs), fuse/divide can enable game-changing architecture changes.

2.4.2 The limited potential of reorientation as a game-changing transformation

Research papers originally exploring system transformation identified three of the four transformation principles shown in Figure 1: expand/collapse, fuse/divide, and expose/cover (Singh et al. 2009). The principle of reorientation was introduced later by Haldaman and Parkinson (2010) after noticing that some products could not be completely explained by the three transformation principles. Of the 90 products studied in their work, 11 reconfigured in a way that could not be described by one of the original three principles. However, when we further examined these 11 products, many of the reorientations led to minor changes in system capability.

While it is true that reorientation can be used to achieve different end-states, the *transformative* nature of this configuration change is often minimal. Concept 6, for example, uses reorientation to create a pivot point that allows the amount of downforce generated to be tailored. Other concepts that involved tailoring performance often relied on the facilitator *material flexibility*.

In concepts where material flexibility did not have a presence, the act of reorientation often served as a way of completely changing a component's functionality. Concepts 4 use reorientation to change a wheel from a rolling support into a windmill. Concept 7 relies on reorientation to modify the system's circuitry to carry out a different aspect of the mission. In the end, many of the concepts generated either used reorientation in a secondary role, or required an additional principle to enact the desired change.

Conclusion: The principle of reorientation often serves in a secondary role, or requires an accompanying principle to enact the desired change. When considered alone, a reorientation minimally impacts overall system architecture. However, this principle may be needed to assist a planned configuration change driven by another principle.

2.4.3 The significance of expand/collapse and expose/cover

In our study, the principle of fuse/divide often facilitated one-time transition changes. That is, the transformation allowed for different phases of the mission to be carried out, rather than being used to adapt system performance to dynamic terrain. Conversely, reorientation often facilitated repeatable, reversible changes to system configuration. From the concepts above, the remaining two principles (expand/collapse and expose/cover) often accommodated both transition types.

As an example of one-time configuration change, tumbleweed-inspired rovers (Expand/collapse concept #9) have been an ongoing project at NCSU since the early 2000's, and are strongly enabled by expand/collapse. These systems are designed for missions that require traveling large distances (100s or 1000s of kilometers) over a wide range of Martian terrain. First, a tumbleweed rover is expanded before deployment. Sending this rover in a collapsed state allows a maximum number of systems to be packed into the launch fairing. Additionally, as shown in Expand/collapse concept #10, these systems can use sails that are expanded / collapsed to provide start/stop and steering capabilities that increase the rover's science gathering ability. This represents a reconfigurable change to the system to tailor system performance as a function of time.

Further, we often saw coupling between transformation principles. For instance, many of the reorientation concepts were aided by the transformation principle expand/collapse. At times, expand/collapse was aided by reorientation. As an example, a glider concept was generated (Expand/collapse concept #2) to operate in the Melas Chasma on Mars. Given the atmospheric differences between Earth and Mars, the length of the wing needed for the glider design was a significant design challenge. To address this challenge, the transformation principle of expand / collapse was used to extend the wings for flight from a stored state. The nature of the motion, however, required a degree of rotation, which we have classified as a transformation principle of reorientation. This motion is considered an expansion as there is a significant change in overall system geometry. Reorientation is used in a supporting role. We view this coupling as a significant outcome that is further discussed in Section 2.4.5.

Overall, the concepts generated using the principles of expand / collapse and expose / cover offered the most significant realm of possibilities. By facilitating one-time changes to accommodate different mission phases and the ability to fine tune system configurations to meet changes in the operating environment (such as the transition between rolling / roving in Expose / cover concept #6) the greatest design freedom was found in these concepts.

Conclusion: When looking for a revolutionary way to re-envision planetary exploration vehicle design, the principles of expand/collapse and expose/cover offer game-changing capabilities. While they may be used in tandem with other transformations, these two principles typically serve as the main driver of significant performance modification. Concepts generated should embrace these two principles where possible.

2.4.4 Repeatable and reversible versus one-time configuration changes

By definition, a reconfiguration must be repeatable and reversible [3]. Reconfigurability, therefore, is a special subset of transformations. While beneficial in many scenarios, the reversibility and repeatability of a transformation is not always necessary. Unlike an umbrella – an application of the expand/collapse principle – which has two distinct states between which the user is constantly operating - some of the proposed concepts solved packaging challenges with one-time configuration changes.

The glider in Expand / collapse concept 3, for instance, is an example of a one-time configuration change. The tail section begins in a collapsed state purely for packaging and transport purposes. At time of launch, the tail extends. While it is possible to design this transformation in a way that enables repeatability and reversibility, there is no apparent justification for this need. Primarily, these one-time configuration changes occurred at mission phase transitions or at the beginning / end of a mission plan. The performance impact of these configuration changes is significant. They enable a go / no-go ability for the system. Without these transformations, a concept would not meet the minimum performance threshold necessary.

Conversely, reconfigurability provides opportunities to tailor system performance to changing operating conditions or terrain properties. The performance impact of these reconfigurations often increases the likelihood of mission success or extends system capabilities. Significantly, but not necessarily unexpected, every reorientation concept can be characterized as a reconfiguration. Similar behavior can be seen in the expose / cover principle, where all but one of the concepts could be considered a reconfigurable transformation. Yet, only two of the fuse / divide concepts (Concepts 2 and 6) either required or could enable reconfigurability. Expand / collapse proved a more difficult principle to characterize from the concepts generated in this study. Expansions can definitely promote reconfigurations, unless they are used to bring out configuration changes associated transitioning from a packed state to a deployed state.

Conclusion: The ability to reconfigure can allow a system to adapt to various operating conditions. However, one-time transitions can have enormous impacts at mission phase transitions. Therefore, designers should consider one-time transformations when undergoing paradigm changes in operation. Reconfigurability should be explored when the transitions are in response to localized operational changes.

2.4.5 Lack of orthogonality between transformation principles / facilitators

At the beginning of this project, the plan developed by the research team called for the development of concepts using transformation principles to guide the brainstorming process. It is important to note that this is the original intent of the transformation principles. Presenting a designer, or team, with the transformation principles and facilitators (including definitions, text examples, and pictures) allows the mind to construct concepts that may not have been previously considered. Essentially, this forces a person to reassess the mental model with which they approach the problem.

Using transformation principles and facilitators as the foundation of a classification scheme is more challenging. Many times during the investigation, members of the research team debated the classification of a concept. This debate was often brought about by the experiences and perspectives of each member of the team. Further, many of the transformations utilized multiple principles and / or facilitators.

We suggest that, regardless of how a concept is classified, that the exercise of classifying concepts is enlightening and provides significant insight into problem complexity and opportunities for true innovation. Concepts using a single principle and facilitator (such as Reorientation concept 1) are not terribly innovative and lead to "small" changes in overall architecture. The concepts that effectively blur the lines between principles, or actually use multiple principles, offer the most innovative (and challenging) opportunities for configuration changes and performance gains.

Conclusion: Though created as a brainstorming tool, transformation principles and facilitators can be used as a classification tool, despite a lack of true orthogonality. Analysis of the concepts presented above suggests that the classification assigned to a concept is not as significant as identifying those concepts who blur the lines – or use multiple – transformation principles. It is these concepts that potentially offer the most innovative solutions and the greatest chance for significant performance benefits.

Having highlighted the higher-level conclusions from the systematic study of transformations, the next section of this report discusses the development of three architecture concepts that came from this effort. These concepts are primarily driven by the principles of expand/collapse or expose/cover, and use both one-time and reconfigurable transitions. For each concept, the mission profile, system architecture, completed analyses, and priority technical challenges remaining are introduced and discussed.

3. Preliminary development and initial analysis of three system concepts

The concepts introduced in Section 2 were generated by 11 undergraduate and 3 graduate students at North Carolina State University. The undergraduate students were seniors who represented three design teams participating in their capstone design experience. The graduate students were funded under this Phase 1 effort and were advised by the PI and Co-PI. The graduate students also worked with the undergraduate design teams to provide expertise, insights, and raise questions about architecture decisions that were made during the year-long capstone experience.

The following subsections discuss three concepts deemed most promising by the research team. In choosing the concepts to develop and present in this report, the research team considered the following:

- diversity of targeted missions within the product portfolio;
- concepts requiring multiple transformations (one-time and reconfigurable);
- concepts that blurred the line between transformation principles and transformation facilitators;
- concepts that supported the conclusions developed in Section 2.4;
- quality of work achieved in developing the proposed concept.

In each subsection, the mission profile is introduced and the required architecture changes are discussed in an operational context. The analyses completed to assess technical feasibility of each concept are presented, and remaining technical challenges/questions are highlighted.

3.1 Concept 1 – Exploration of Valles Marineris – Air Cannon

<u>Mission profile:</u>

This concept is designed to explore Valles Marineris, with a proposed landing site located in a crater at the head of the canyon. Exploration will occur via aerial exploration vehicles that are launched from a compressed air cannon. These vehicles will have a minimum level flight range of 1,000 km, allowing them to explore the top half of Valles Marineris. This site is valuable because exploring the canyon walls provides an opportunity to investigate the stratigraphy of Martian rock, directly addressing Mars Exploration Program Analysis Group (MEPAG) Goals II.C.2 and III.A.1. MEPAG Goal II.A.4 will also be investigated since flying vehicles provide an excellent platform for atmospheric sensing (MEPAG 2010).

<u>Concept of operation:</u>

An aeroshell is used to protect the air cannon and aerial vehicles upon atmospheric entry. The system lands in a folded state, with the aerial vehicles stowed in ballistic shells around it, as shown in Figure 10. Power for the air cannon is provided by an Advanced Stirling Radioisotope Generator. To exploit the readily available CO_2 in the Martian atmosphere, a high pressure compressor provides the propulsive force that launches the ballistic shells. A pressure tank surrounds the barrel to store energy until firing. It is separated from the barrel by a high-speed firing valve. The cannon is designed to have 150 W of electrical energy available. Its base load will be approximately 30 W with 120 W remaining to run the compressor and maneuver the cannon.

The transformation principle ***reorientation*** is used to: 1) unfold the cannon after landing, 2) reposition the cannon for charging, 3) load the ballistic shells, and 4) position for firing. After unfolding, the pressure chamber is evacuated and the air cannon reconfigures so that the first ballistic shell is in the muzzle. The firing valve opens, drawing the ballistic shell down to the bottom of the barrel. The firing valve closes and the pressure tank is pressurized to 2 MPa. When reoriented into the desired firing direction, the firing valve is opened and the ballistic shell is expelled as shown in Figure 11.

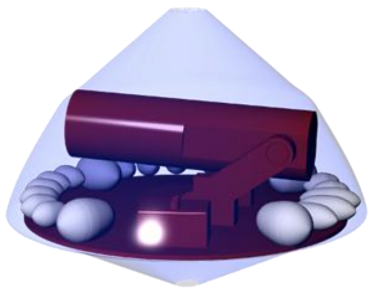


Figure 10. Air cannon and ballistic shells packaged for atmospheric entry

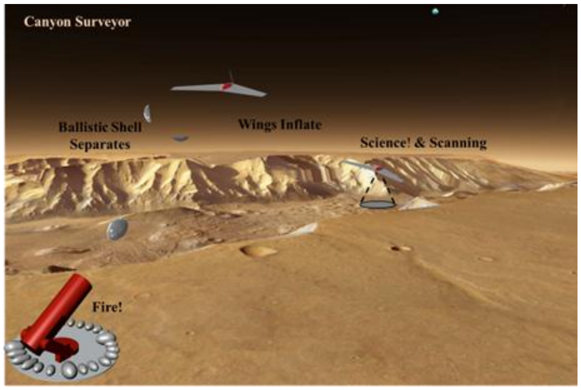


Figure 11. Illustration of aerial vehicle launch and candidate mission

The shell flies ballistically until the velocity is sufficiently reduced to allow for safe aircraft deployment. An initial analysis of the ballistic flight path suggests this occurs at a velocity around 140 m/s, and at an altitude above 200 m. At this point, the ballistic shell ***divides*** and falls away from the aerial vehicle inside. Two airplane architectures have been selected, shown in Figure 12, using the transformation principle ***expand/collapse*** to deploy.

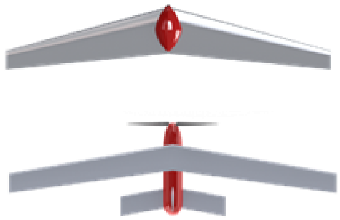


Figure 12. Representation of the two aerial vehicle architectures

The first vehicle architecture is an inflatable flying wing. This architecture uses on-board batteries and a CO_2 canister charged by the ground station prior to launch. Thrust comes from a large propeller that uses the principle of ***expose/cover*** to fold out from the sides of the airplane body. When the fairing opens, this plane rapidly inflates and powers up its propeller to begin its flying mission.

The second aircraft architecture is significantly more rigid. For this design, the wings fold back along the fuselage and the transformation principle ***expand/collapse*** is used to actuate them to their flight position after the ballistic shell opens.

Four mission profiles have been specified for these aerial vehicles:

- Surveying the Martian atmosphere using the inflatable aerial architecture. These craft are optimized for high endurance flight (time).
- Surveying the canyon by exploring the surface and walls while in flight. These craft are optimized for maximum range (distance).
- Transporting a Micro Lightweight Survivable Rover to the canyon floor for additional scientific investigation using the fold-out aerial architecture.
- Landing on the cliff face. These craft will be equipped with a microspine attachment system and retractable propeller, both enabled by the principle ***expose/cover***.

<u>Supporting analysis:</u>

Mass budgets are an essential component of all conceptual design. The breakdown of the system into its subsystems is shown in Table 1. Twenty-one aerial vehicle architectures can be included to give a total down mass of 695 kg. This target was selected to ensure current landing technologies could be used on this mission. A mass growth rate of 50% was also applied. These estimates were built up from the plane configurations, the desired scientific payloads, and estimates of the mass of energy supplying devices, computers, and other subsystems. Figure 13 shows the breakdown by mass. Similar studies were done for each of the subsystems including all aerial explorer architectures and the cannon station.

Table 1. Mission breakdown and subsystem mass

Component	Quantity	Mass (kg)
Ground station	1	137
Atmospheric surveyor	6	78
Canyon surveyor	8	120
Canyon lander	3	61
Cliff lander	4	67
Subtotal	**-**	**463**
Mass growth	50%	232
Total	**21**	**695**

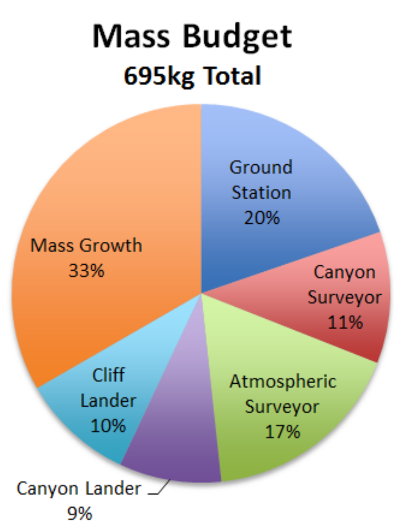


Figure 13. System mass breakdown

Flat plate wing assumptions were used to determine the initial configurations of the aerial architectures. Tables of performance characteristics at various flight speeds were created and the regimes offering the best performance for the desired objective was chosen. The rest of the configuration parameters were calculated based on this selection. The considerations included calculations of Reynolds and Mach regimes, estimates of propeller sizes, wing lengths, and aspect ratios as well as system mass and power required. Aerial architectures have also been analyzed for estimates of flight time, distance, payload, and operating altitude. These calculations were completed using properties of available batteries, motors, and propellers. Table 2 summarizes of the configuration analyses.

Table 2. Aerial Explorer configuration analysis

Assumptions:	Steady-Level Flight (L=WT)				
	Battery Powered				
	Traditional Propeller Config.				
	Canyon Surveyor	**Atmospheric Surveyor**	**Canyon Lander**	**Cliff Lander**	
b =	**3.00**	**3.00**	**3.00**	**3.00**	**m**
AR =	**15.00**	**18.00**	**15.00**	**15.00**	**--**
s =	0.60	0.50	0.60	0.60	**m^2**
e =	**0.70**	**0.70**	**0.70**	**0.70**	**--**
c =	0.20	0.17	0.20	0.20	**m**
Mass Total =	**13.02**	**15.02**	**20.25**	**16.71**	**kg**
WT Total =	48.30	55.72	75.13	61.99	**N**
Cd,0 =	**0.03**	**0.03**	**0.03**	**0.03**	**--**
Battery Cap =	**1500.00**	**1500.00**	**1500.00**	**1500.00**	**W-hr**
Prop Efficiency =	**0.70**	**0.70**	**0.70**	**0.70**	**--**
Motor Efficiency =	**0.90**	**0.90**	**0.90**	**0.90**	**--**
Max Endurance =	**3.561**	**3.008**	**1.836**	**2.450**	**hrs**
Power Setting @ Max E =	**265.350**	**314.143**	**514.741**	**385.716**	**Watts**
Mach # @ Max E =	**0.327**	**0.368**	**0.408**	**0.368**	**--**
Max Range =	**1167.370**	**1108.364**	**750.753**	**909.070**	**km**
Power Setting @ Max R =	**305.996**	**352.980**	**589.089**	**449.074**	**Watts**
Mach # @ Max R =	**0.429**	**0.470**	**0.531**	**0.490**	**--**

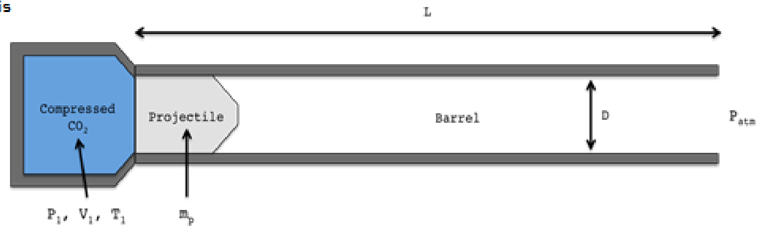
Conceptual three-dimensional models of all aerial architectures and the air cannon have been created in Vehicle Sketch Pad and/or Solid Works. Proof-of-concept level work has been completed to demonstrate that the deflated aerial architectures can be packaged in the allotted space. Detailed packaging analysis and kinematics of the transformation remain to be completed.

A model of the air cannon internal fluid problem was built to relate several design variables including the firing tank volume, the cannon size and shape, the projectile mass, and the firing pressure to the exit velocity of the projectile. An illustration of this model is shown in Figure 14. The exit velocity of the projectile and the firing angle are the inputs to an external ballistics model used to predict the two-dimensional motion of the projectile through Mars' atmosphere. The external ballistic model is illustrated in Figure 15.

Motion of a Projectile Within A Barrel

Thermodynamic Closed System Analysis

mp =	13.02	kg
L =	3.00	m
D =	0.50	m
P_1 =	2.00	MPa
P_1 =	290.08	psi
V_1 =	4.00E+00	m^3
T_1 =	300.15	K
Tc (CO2) =	304.19	K
Pc (CO2) =	7380.00	kPa
R_u =	8.31	J/mol-K
P_{atm} =	1.16	kPa
MWco2 =	44.01	g/mol
A =	0.20	m^2
V_2 =	4.59	m^3
P_2 =	1.74	Mpa
P_2 =	252.84	psi
T_{R1} =	0.99	--
P_{R1} =	0.27	--
Z_1 =	1.00	--
T_{R2} =	0.99	--
P_{R2} =	0.24	--
Z_2 =	1.00	--
n =	3.21E+03	# moles
mCO_2 =	1.41E+05	g
Wp =	1.10E+06	J
Wsurr =	680.35	J
Wnet =	-1.10E+06	J
v_{ext} =	410.75	m/s
Mach # =	1.677439379	--
t_{ext} =	0.05	s
g's $_{Earth}$ =	837.4139673	--



Assumptions: Quasi-Equilibrium Process
Gas behaves like and Ideal Gas (from compressibiliy EOS)
Gas expands isothermally
No heat exchanged
No change in internal energy
Neglect change in PE
Will estimate travel time for projectile to exit barrel

Conversions: 1 Mpa = 145.0377 psi

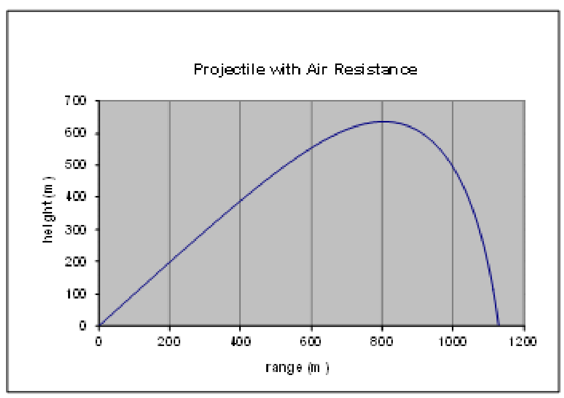
Figure 14. Internal ballistics model

Motion of a Projectile Under Gravity with Air Resistance

Projectile fired at speed v at angle theta degrees to horizontal
Air resistance = kv^2

v =	410.75	m/s
theta =	45.00	degrees
g =	3.71	m/s^2
delta_t =	0.05	s
rho =	0.01503	kg/m^3
A (x_section) =	1	m^2
k =	2.25E-03	--
v_x_init =	290.45	m/s
v_y_init =	290.45	m/s
Max Range =	1129.07	m
Max Height =	636.10	m
Range @ Max Height =	804.34	m
Time @ Max Range =	36.10	s
Time @ Max Height =	12.35	s
Height @ Wing Deployment =	436.49	m
Range @ Wing Deployment =	452.38	m
Time @ Wing Deployment =	3.55	s

slider



Assumptions: No wave drag
k value chosen based on spherical geometry

Figure 15. External ballistics model

<u>Priority technical challenges / questions to be addressed:</u>

1. Model aerial vehicle packaging and deployment from ballistic shell;
2. Develop models to demonstrate flight capabilities such as range and maneuverability;
3. Build proof-of-concept prototypes that demonstrate air cannon operation and the deployment of the aerial vehicles from the ballistic shells;
4. Validate the technical feasibility of the cliff landing procedure described above.

3.2 Concept 2 – Exploration of Hellas Basin - Transforming Roving-Rolling Explorer (TRREx)

<u>Mission profile:</u>

This concept is designed to facilitate planetary exploration of locations that have flat areas, gentle gradients and steep slopes. This concept is particularly attractive, as traditional rocker-bogie architectures have difficulty maneuvering down steep slopes. Example exploration sites comprised of such terrain are the Hellas Basin and the Tharsis region. A landing site is chosen that is at an elevated altitude relative to the planned mission path to maximize potential energy advantages. In the Hellas Basin, the landing site selected is at the edge of the crater. The mission path is hundreds of kilometers long, since the Basin is over 2000 km in diameter and 8 km deep.

<u>Concept of operation:</u>

When searching for novel rover designs, inspiration can be drawn from nature. For example, the golden wheel spider uses the transformation principle ***expand/collapse*** to take advantage of the dynamics of a sphere rolling down a hill (Armour and Vincent 2006). The *TRREx* rover builds on this motivating example by: 1) traversing in a standard wheeled configuration over conventional terrain and 2) rolling as a sphere down steep inclines or over rough terrain. The transformation between these two primary end-states is depicted in Figure 16. Though depicted as a discrete process, the reconfiguration is done in a continuous manner.

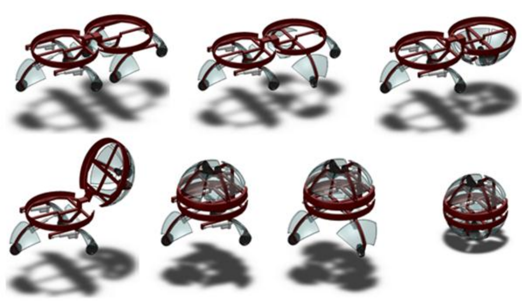


Figure 16. *TRREx* transformation using the principle expand/collapse

In free-rolling mode, the *TRREx* has a spherical shape. To enable actuated- or guided-rolling, each hemisphere has four independently actuated "quarters" that allow for dynamic modification of the center of gravity. This capability becomes significant when no gradient is present, as actuated and controlled rolling become necessary to begin motion. As shown in Figure 17, this transformative reconfiguration is made possible by the transformation principle ***expose/cover***.

Requirements for this system include that it must operate for a minimum of 120 sols on Mars while traveling at least 800 km during its operational life. Minimum expectations for rolling and roving velocity are 0.5 m/s and 0.05 m/s, respectively.

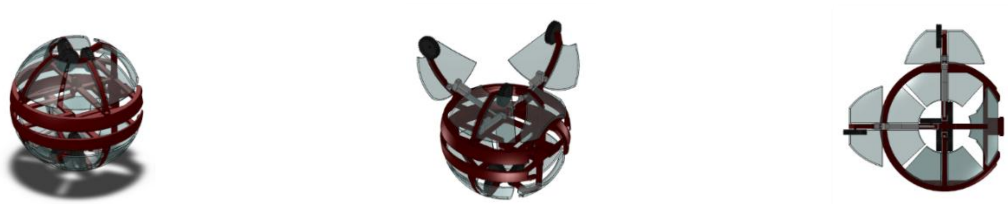


Figure 17. *TRREx* transformation using the principle expose/cover

Supporting analysis:

The objective of initial analysis was to develop a mathematical model in terms of rover design parameters. This model would then be validated with physical experiments using several physical prototypes. Once validated, the mathematical model could then be used to perform parametric studies and answer questions about various performance aspects of the rover. For this concept, three models are required to completely describe the rover:

- a model of roving that includes the dynamic interaction of the active suspension with the terrain;
- a model of transformation that represents the dynamic interactions between the rover and its environment during the actuation-phase;
- a model for rolling that should include the interaction of the spherical rover with the terrain in 'free rolling' and the ability to describe the impact of the actuated legs.

Choosing a model to develop was the first challenge addressed. Active suspensions are not novel and roving has been extensively studied in the literature. Modeling the transformation is necessary, but it does not provide immediate insight into the critical locomotive performance of the system. The rolling mode, however, is mostly unexplored especially when the notion of self-propelled motion is incorporated into the design of the system. Additionally, mathematical models predicting the behavior of a sphere traversing terrain features like slopes, craters, ravines, channels and rock-fields under the influence of wind and gravity have been previously developed by the research team. These models were easily modified to be applicable to the TRREx in 'free rolling' mode. Unexplored, however, was the specific problem of actuated rolling and, it was decided that modeling this would serve to mature the concept.

Modeling actuated rolling is more complicated than free rolling in that control inputs can be used to control the dynamics of the system. Rather than starting with a three-dimensional problem, initial efforts focused on a two-dimensional representation of the system. The information gathered in this analysis can then be used to establish mathematical and experimental correlations between the size and weight of the rover and the friction, slopes or obstacles that it can overcome.

A 2-D representation of the *TRREx* system, as shown in Figure 18, is suspended on a stand via a rotational bearing and has four legs that can be actuated by linear motors. When any one (or more) of the legs are opened, the effective center of mass is offset and the system rotates about the axis. If the sequence of actuations of the legs is such that the center of mass of the system is always maintained in front of the axis of rotation, then a continuous rotation is achieved. Figure 19 shows the continuous rotation predicted by the numerical model.

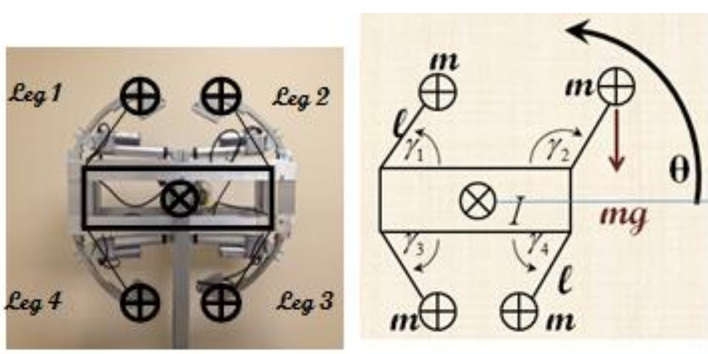


Figure 18. 2-D physical prototype of *TRREx* system and lumped parameter model

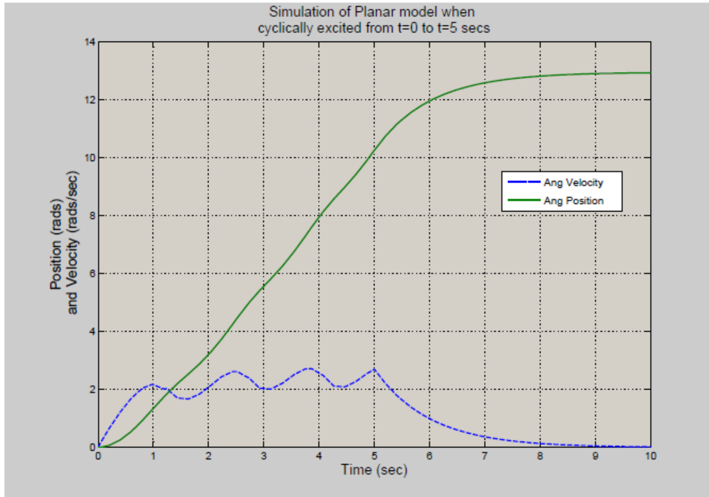


Figure 19. Cyclic actuation of the legs to produce continuous rolling

Using Newton-Euler methods or Lagrange's method, the equation of motion that describes the motion of the one dimensional system can be shown to be:

$$\ddot{\theta} = \frac{mgl}{I}(-\cos\gamma_1 + \cos\gamma_2 + \cos\gamma_3 - \cos\gamma_4)\cos\theta + \frac{mgl}{I}(\sin\gamma_1 + \sin\gamma_2 - \sin\gamma_3 - \sin\gamma_4)\sin\theta - C\dot{\theta} \qquad [1]$$

Where m is the effective mass at each leg, g is the local gravity parameter, l is the length of the effective leg, I is the total rotational moment of inertia of the system and C is the overall damping in the system. The angle θ is the rotational position of the system and the γ's are the angles that define how 'open' a leg is with respect to the frame (note that some γ's are measured in the clockwise direction while others are measured in the counterclockwise direction). If all the γ's are the same then the effective center of mass is on the axis of rotation and there is no moment that produces rotation. If one of the legs is more open (with respect to the others) then there is moment that creates rotation as described by the equation of motion. Also note that the rotational moment of inertia is a varying function of time as the legs open and close, but this change is assumed to be small compare to the overall inertia.

The system can be written in state-space as:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= KA\cos x_1 + KB\sin x_1 - Cx_2 \end{aligned} \qquad [2]$$

where,

$$\begin{aligned} K &= \frac{mgl}{I} \\ A &= (-\cos\gamma_1 + \cos\gamma_2 + \cos\gamma_3 - \cos\gamma_4) \\ B &= (\sin\gamma_1 + \sin\gamma_2 - \sin\gamma_3 - \sin\gamma_4) \end{aligned}$$

Thus we see that the dynamics are non-linear in the state variables and our physical system is such that we do not wish to operate about a set point, therefore we cannot linearize the equations. Also the control u= $[\gamma_1, \gamma_2, \gamma_3, \gamma_4]^T$ enters the system nonlinearly. Thus linear control theory cannot be used and numerical optimization must be used.

Finding the optimal control scheme for this state-space formulation can be achieved by minimizing a quadratic cost function associated with transferring the system from point A to point B, as shown in Figure 20. The cost function can be represented by:

$$J = (x(t_1) - x_1)^T \rho (x(t_1) - x_1) + \int_{t_0}^{t_1} (u^T R u) dt \qquad [3]$$

Figure 20. Motion of the system from initial to final point

The first term in this quadratic cost function is a penalty for missing the final target state. The second term is the total control effort spent (amount of actuation required) to achieve the target. Minimizing Equation 3 is inherently constrained by the dynamics of the system as described in Equation 2. Weights on the penalty term for missing the desired position can be different from the penalty associated with missing the desired velocity. This weight matrix is explicitly diagonal if these relationships are not coupled, as shown in Equation 4.

$$\rho = \begin{bmatrix} \rho_p & 0 \\ 0 & \rho_v \end{bmatrix} \qquad [4]$$

Further, when characterizing the control effort, it is assumed that it is unnecessary to weight the actuation of any one leg different than any other. Thus, all inputs in u are equally weighted by the parameter r.

$$u = \begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \gamma_3 \\ \gamma_4 \end{bmatrix} \qquad R = r \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad [5]$$

The input angles u= $[\gamma_1, \gamma_2, \gamma_3, \gamma_4]^T$ for the suspended two-dimensional system are constrained by physical interference to be between 45 and 90 degrees. This turns the problem into a constrained nonlinear optimization problem. For a two-dimensional model rolling on the ground, additional constraints on the inputs should be added to ensure there is no physical interference between an open leg and the ground.

The control input is broken down in N time steps. The control values can switch discretely between time steps in a piecewise continuous parameterization, or they can linearly change using the parameterization of a continuous linear spline. The constrained non-linear optimization problem is solved until either a minima (up to a user defined tolerance) is satisfied, or until any other user defined stopping criterion are met. The cost function defined in Equation 3 may have multiple minima, and the optimization will be driven in the direction of the minimum closest to the initial guess. This may result in the solution being a local minimum. Multiple starting points are used to increase the likelihood of identifying the global minimum for the problem formulation.

Various scenarios using different system, problem, and control parameters were run. In the first scenario, the problem is solved using a piecewise continuous control parameterization. The system moves from an initial point to a final point that is one revolution away. It is desired to reach this location with a no final velocity, but the weight matrix only has a value for final position. The complete set of parameters for this scenario is listed in Table 3. The optimized control on the four legs and the corresponding system response to this optimum control is shown in Figure 21.

Table 3. Optimized control for scenario 1

System Parameters	*Symbol*	*Value*	*Units*
Offset masses on legs	m	0.5	Kg
Rotational inertia	I	0.75	$Kg\text{-}m^2$
Gravity	g	9.8	m/s^2
Length of leg	l	0.3	m
Damping	C	1	Kg/s
Optimization Parameters		*Value*	
Number of pieces		N=8	
Parameterization type		Piecewise continuous	
Weight on control effort		r=1	
Weight on end point tolerances		ρ_p=10, ρ_v=0	
Problem Parameters	*Initial*	*Final*	*Units*
Time	0	4	seconds
Position	(0,0)	(360,0)	(Deg, Deg/sec)

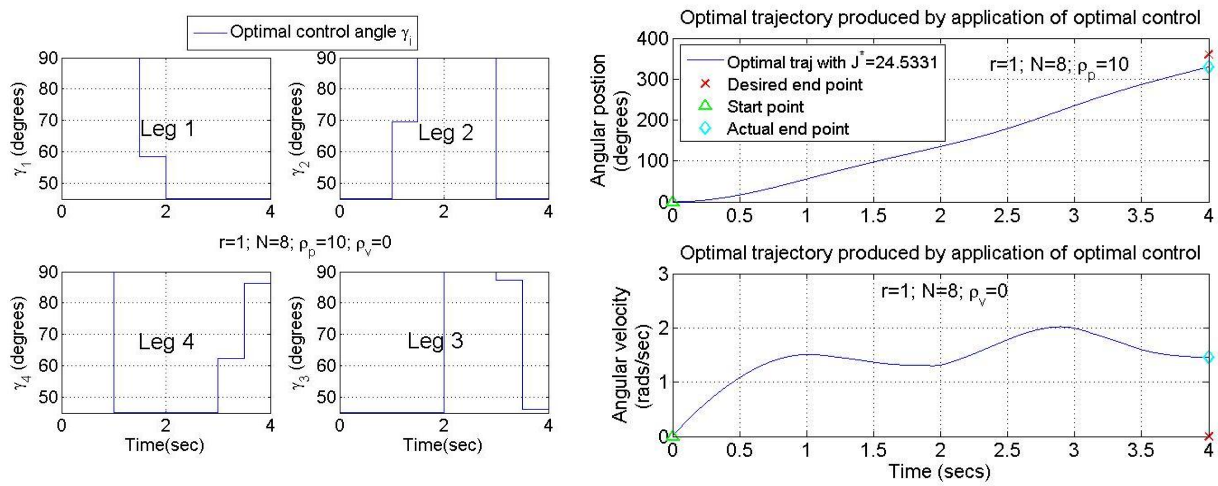


Figure 21. Simulation results for scenario 1

The control solution starts the system with legs 1 and 4 fully open (at 90 degrees) and legs 2 and 3 closed (at 45 degrees). After 1 second at an angular position of about 50 degrees, leg 4 closes and leg 2 opens. At 2 seconds and an angular position of about 130 degrees, leg 1 closes and leg 3 opens. The next procedure is to close leg 2 and open leg 4, actuating the legs in a cyclic fashion. This control solution moves the system at a fast speed, as it takes 4 seconds to complete the revolution. Note that the final velocity was not penalized, and a weight on final velocity would have introduced a 'braking' actuation that would disrupt the cyclic pattern of leg movement.

A second demonstration scenario changes the control scheme using a continuous linear spline. Here, the system is required to execute three revolutions in three seconds. To make this possible, the inertia of the system is reduced. The results for this demonstration are shown in Table 4 and Figure 22, indicating that the system is able to achieve higher velocities while getting close to the desired end point within the tolerances determined by the weights in the cost function.

Table 4. Optimized control for scenario 2

System Parameters	*Symbol*	*Value*	*Units*
Offset masses on legs	m	0.5	Kg
Rotational inertia	I	0.125	$Kg\text{-}m^2$
Gravity	g	9.8	m/s^2
Length of leg	l	0.3	m
Damping	C	1	Kg/s
Optimization Parameters		*Value*	
Number of pieces		N=8	
Parameterization type		Continuous linear spline	
Weight on control effort		r=1	
Weight on end point tolerances		ρ_p=10, ρ_v=0	
Problem Parameters	*Initial*	*Final*	*Units*
Time	0	3	seconds
Position	(0,0)	(6π,0)	(Rads, Rads/sec)

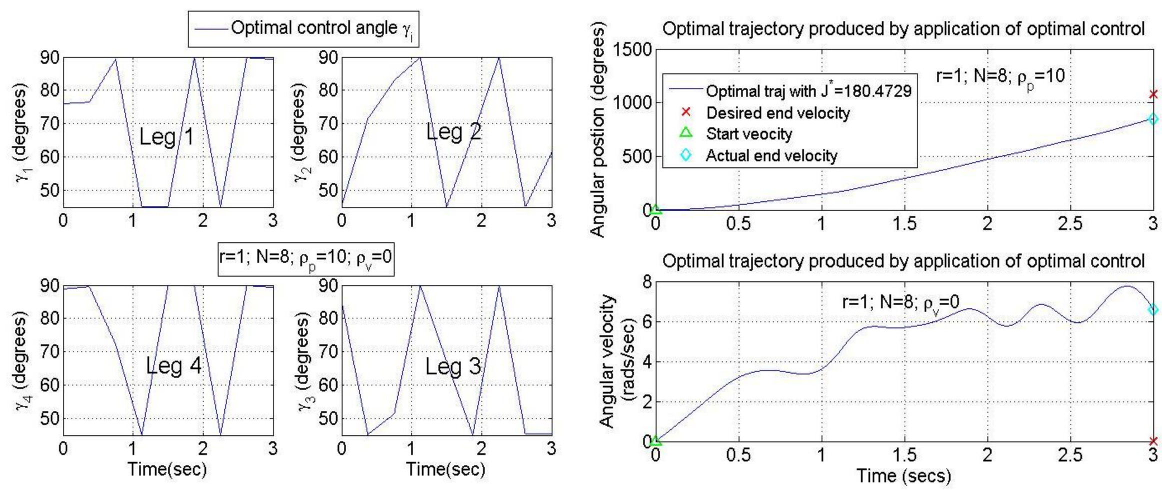


Figure 22. Simulation results for scenario 2

A physical prototype of this model was also developed to begin model verification. The prototype has been constructed so that it can be easily expanded to a three-dimensional version, as shown in Figure 23. The frame and the legs are made of aluminum. The actuators that open and close the legs are linear motors with potentiometer feedback. The angle of the system is detected by using a 3-D accelerometer which is input into the controller. To handle the complex control schemes of the eventual 3-D system model, a NI single board RIO – 9611 controller was selected. The whole system is suspended on an axle on an aluminum frame so as the legs open the system rotates about this axle. For future experiments marine grade wooden support wheels (Marine grade plywood was chosen for its strength to weight) are attached to the sides so that the system can roll on flat ground. Figure 24 shows the developed software used to program the controller.

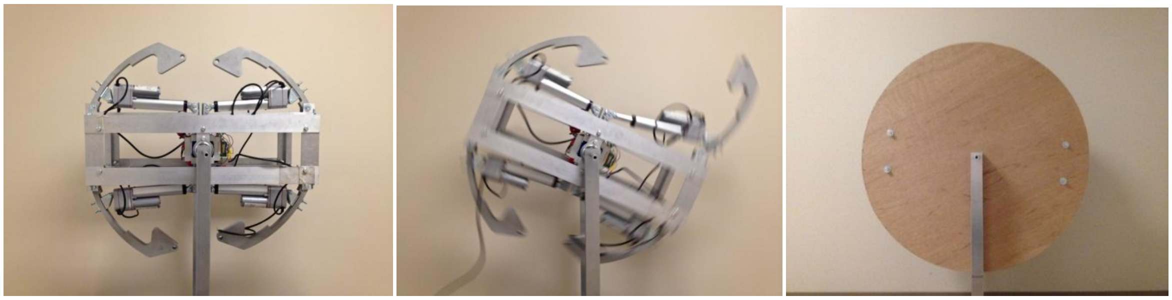


Figure 23. Physical prototype

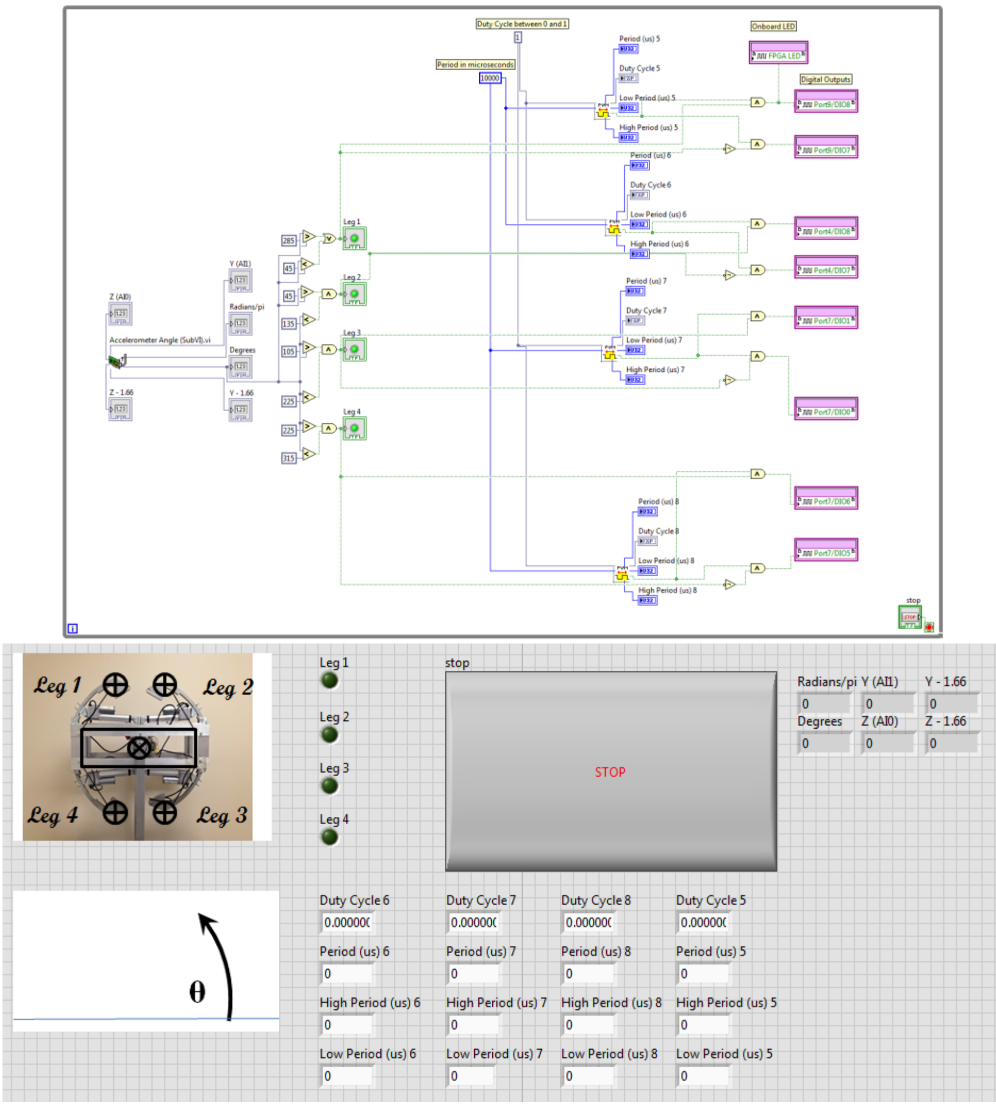


Figure 24. Main VI and front panel in Lab-view used to program the controller

Priority technical challenges / questions to be addressed:

1. Ensure proper actuation of rover legs during actuated- and guided-rolling;
2. Develop analytical and physical models of the three-dimensional system;
3. Perform tradespace analysis of system to define effective system properties.

3.3 Concept 3 – Exploration of Melas Chasma – Glider and base architectures

Mission profile:

This concept is designed to explore Melas Chasma, an 11 km deep trench in Valles Marineris near the equator of Mars. It is believed to be an ancient lakebed, and was one of the sites considered for the MSL. The objective of this mission is to land a system that is capable of launching a glider into Melas Chasma. Three micro rovers are then deployed on the canyon floor, with science performed at both locations.

Concept of operation:

The system is launched using an Atlas V rocket and travels to Mars in the 500 series payload shroud. Final landing uses a sky-crane, and a base system carries the glider across sand dunes to the top of Melas Chasma. Initial designs specify the base system with a tracked rocker-bogie architecture. Exploring transformations for this architecture is future work.

As shown in Figure 25, the glider is initially compacted to fit within the payload shroud. The transformation principle of ***expand/collapse*** is used to extend both the wings and tail for flight. At the top of the canyon, ***fuse/divide*** is used to separate the glider from the base component. Rocket engines are used to attain necessary launch speed after the base component ***reorients*** to the desired launch angle. The glider then descends into the chasm where it performs a pull-up maneuver to stall the craft. Descent then occurs using hydrazine retro-thrusters, with the wings being jettisoned using the principle ***fuse/divide***.

Three micro rovers are then deployed at the bottom of the chasm. These systems communicate with the base component, allowing for simultaneous experiments to be conducted above the chasm and at the chasm floor.

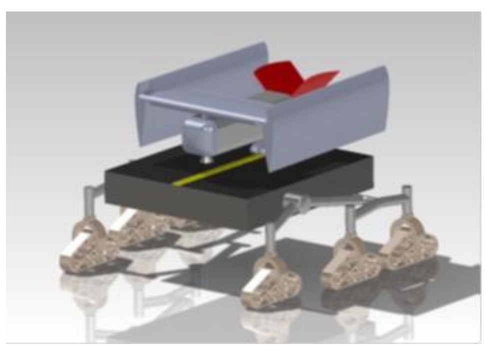


Figure 25. Glider and base architectures

Supporting analysis:

Initial concept selection began by analyzing the sketches for common characteristics and differentiating elements. Specific attention was directed to identifying when key technologies were used in multiple concepts. Metrics representing the properties of mass, complexity, power, and performance were specified and evaluated for each technology. Pugh Concept Selection Matrices (Otto and Wood 2001) were generated as a means of initially down-selecting the concepts for all three phases of the mission.

Though not a mathematically rigorous approach, this process directed discussions that were essential toward identifying those concepts with the greatest potential.

The first phase was dune crossing, the second was descent, and the third was landing. For the dune phase, wheel concepts and suspension concepts were traded. The descent phase traded climbing and flying concepts. Each concept was assigned a score from zero to three in each of several criteria. The score for each concept was the weighted sum of the scores for the attributes. The winning concepts were matt tracks, passive suspension, glider descent, and traditional landing. Later in the design phase the team realized that finding a suitable landing surface for a traditional landing was a much riskier proposition than initially realized. This led to a switch to a dive-stall-fall landing. Table 5 contains the entire Pugh Matrix for this design concept.

Table 5. Pugh Matrix for canyon mission

	Mass	Complexity	Power Required	Reconfigurability	Robustness	Performance	Speed
Metric Weight	4	4	4	4	3	3	3
Tank Tracks	2	1	2	2	2	3	1
Mattracks	1	2	2	3	2	3	2
Deformable Wheels	3	3	2	3	1	2	1
Deflatable Wheels	2	1	1	2	1	2	1
Morphable Treads	2	1	2	3	2	3	2
Hampster Wheel	2	1	3	3	0	1	1
Hovercraft	1	0	0	1	1	3	2
Legged	1	0	1	3	1	3	0
Active Sups	1	2	2	2	3	2	1
Passive Suspens	2	3	3	1	2	1	1
Zipline	1	2	2	1	1	2	3
Winch	2	2	1	2	2	2	1
rappelling	3	1	1	1	1	2	1
Tumbler	3	1	1	1	2	2	1
Swinger	3	1	3	1	1	2	1
TRESSA	1	1	1	3	3	3	1
Gliders	3	2	3	3	2	3	3
Rotor craft	0	0	0	3	1	3	2
Balloons	0	2	1	3	0	2	1
Sky Crane	0	2	0	3	1	3	3
Parafoil	3	3	3	3	0	2	2
Traditional Landing	3	3	3	2	1	3	N/A
Airbag(Dive Stall Fall)	2	2	2	1	1	3	N/A
Cylindrical Airbags	2	2	2	1	1	3	N/A

	Controlability	Maneuverability	Stability	Durability	Feasibility	Weighted Score (out of 99)
Metric Weight	2	2	2	2		
Tank Tracks	2	3	3	2	10	66
Mattracks	3	3	2	2	25	73
Deformable Wheels	1	2	2	1	21	68
Deflatable Wheels	2	2	2	1	17	50
Morphable Treads	1	3	3	2	24	71
Hampster Wheel	0	3	0	2	16	52
Hovercraft	3	3	3	1	18	46
Legged	3	3	2	2	19	52
Active Sups	3	3	3	2	24	68
Passive Suspens	1	1	2	3	20	62
Zipline	2	0	3	2	19	56
Winch	2	1	2	2	19	57
Rappelling	1	1	2	1	15	46
Tumbler	1	1	2	1	16	49
Swinger	1	2	1	1	17	54
TRESSA	3	3	3	2	24	67
Gliders	3	3	2	2	29	88
Rotor craft	2	3	1	1	16	44
Balloons	0	0	3	0	12	39
Sky Crane	3	1	2	1	19	55
Parafoil	0	1	0	1	18	64
Traditional Landing	3	3	2	2	25	76
Airbag(Dive Stall Fall)	1	1	2	1	16	50
Cylindrical Airbags	1	1	2	1	16	50

To derive parametric estimates of the glider configuration, initial efforts focused on the launch and landing profiles. To constrain the size of the glider, external disposable rockets were selected for launch.

A solid rocket motor was selected to minimize complexity. Initial sizing of the glider is shown in Figure 26, with additional properties listed in Table 6.

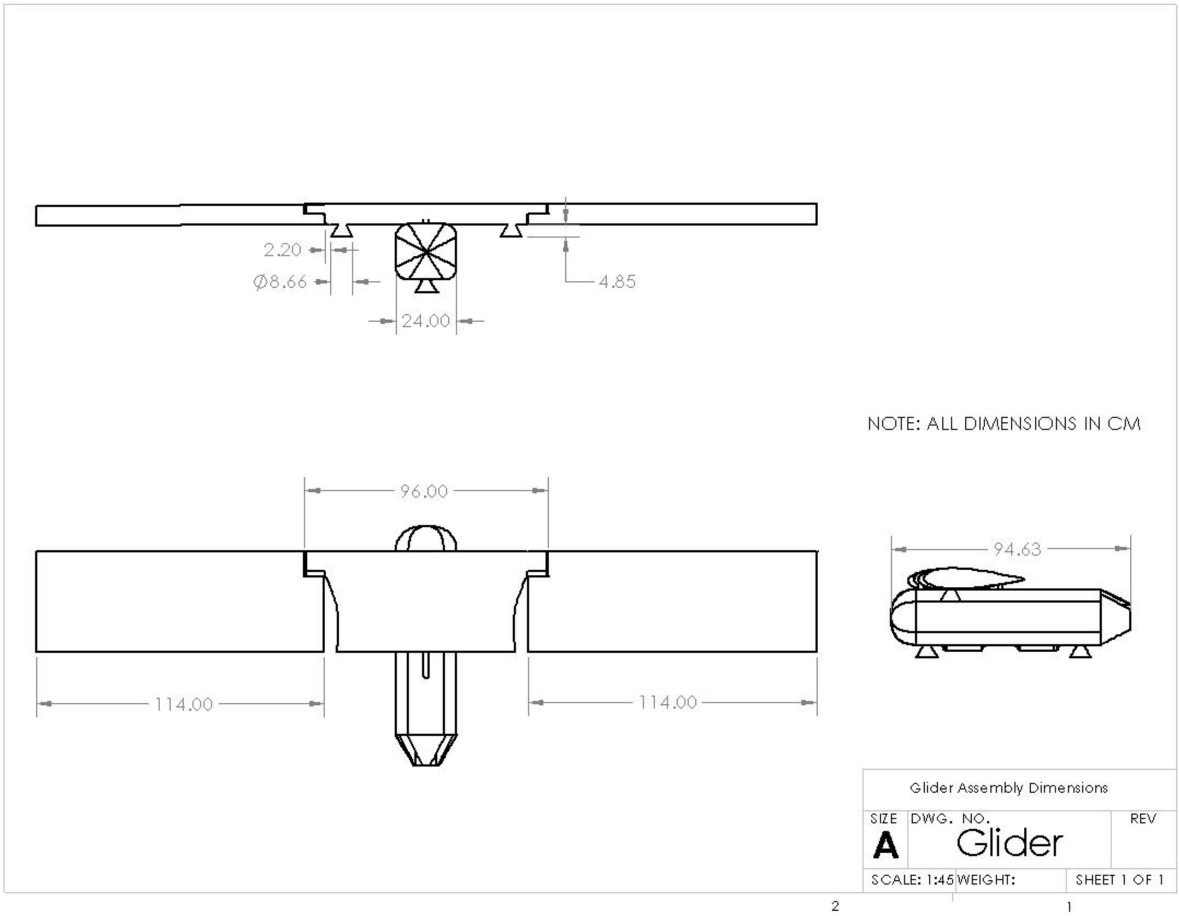


Figure 26. Initial sizing of the glider

Table 6. Basic glider properties

Mass	317.4 kg
Planform area	7.6 m^2
C_L	2.5

Research into small, high-powered rocket motors revealed that two O-class motors could provide enough thrust to launch the maximum set mass of the glider over the canyon. Research into commercially available rockets led to the Cesaroni O8000 rocket motors. Two motors fit the desired need of the system. Table 7 lists the properties of the selected rocket motors.

To control the glider during rocket launch, a reaction control system was chosen for stabilization. Twenty extra gallons of hydrazine fuel was included in fuel calculations to provide short, small bursts from nozzles placed on the bottom on the glider. Further, the slope of the chasm walls was determined to be no greater than a 0.5 m vertical drop per horizontal meter, as illustrated by the red line in Figure 27.Using a ballistic flight profile, the star in this figure represents the point at which the glider is fast enough to sustain flight.

Table 7. Properties of the Cesaroni O8000 rocket motor	
Diameter	161.0 mm
Length	95.7 cm
Total weight	32672 g
Propellant weight	18610 g
Average thrust	8034.5 N
Total impulse	40960 N*s
Burn time	5.1 s
Specific impulse	224 s

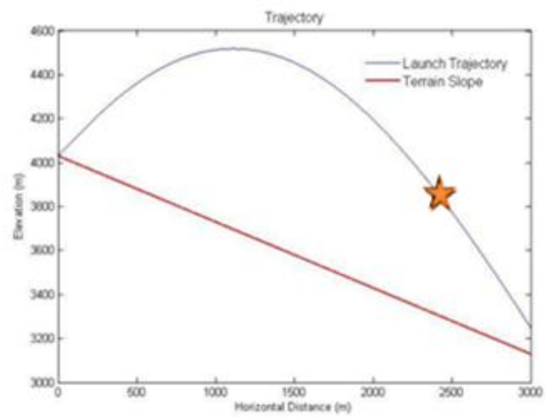


Figure 27. Ballistic launch profile for glider

A variety of controlled descents after the pull-up maneuver were considered with respect to three parameters: time in the descent phase, velocity in the decent phase, and required fuel mass. Plots of height, velocity, acceleration, and total mass of the vehicle as it descended through the retro-thrust phase of landing were also developed.

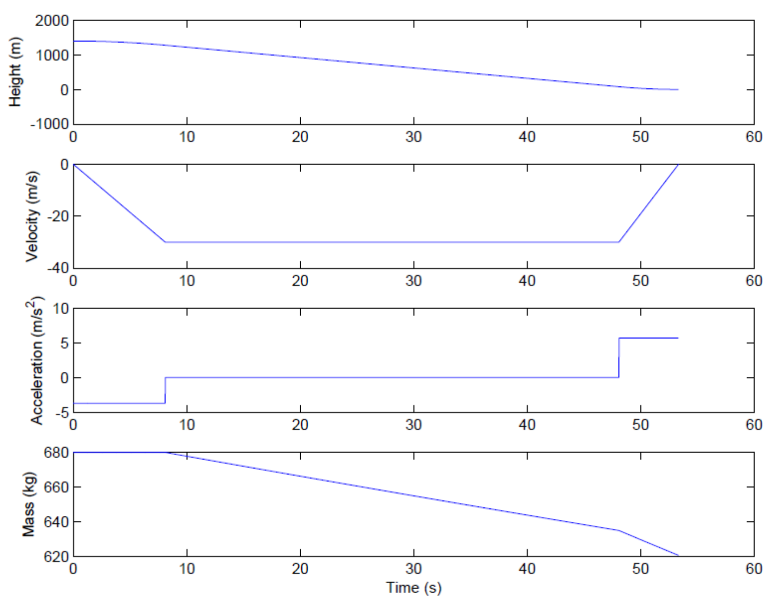


Figure 28. Descent profile

Significant effort was spent analyzing the **expansion** of the wing from the packaged state to the flight stage. Accommodating the system transformation required an intricate folding motion that was achieved using a spherical linkage, as shown in Figure 29. This linkage produces a folding out motion while simultaneously rotating down. A spherical hinge consists of five main parts: three links cut from the surface of a sphere and two rods connected to motors. Two linkages are attached to the rods and free ends are connected to the third linkage. Finally, the third linkage is rigidly attached to the wing, and by rotating the rods from a fixed position, the desire movement can be produced.

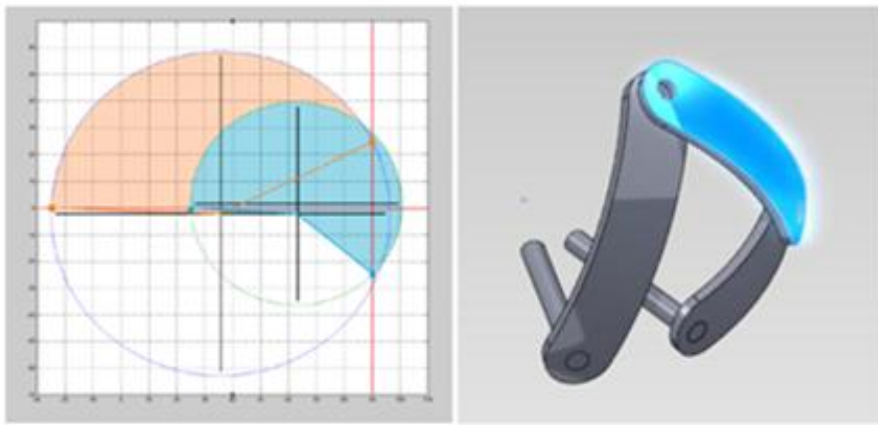


Figure 29. Spherical linkage analysis for glider wing

To provide the necessary movement, the arc lengths of each linkage and the direction in which the rods are pointed must be determined. Due to the nature of the joint, spherical coordinates were used to denote the position of each joint in the three linkages and the direction of the rods were pointing out of the sphere. Because the linkages operate at the same radius, the radial measure of the spherical coordinate could be dropped and the remaining two angles can be plotted against each other. The orange and blue areas in Figure 29 represent the path traced by the left and right linkages, respectively. Given that the starting and ending locations of each linkage is known, the center must be located on a line dissecting the two points. Table 8 shows the final design parameters of the mechanism.

Table 8. Specification of spherical linkage

Arc length of left linkage	60.7^{o}
Arc length of right linkage	37.9^{o}
Arc length of middle linkage	50^{o}
Direction of left rod	35.7^{o} Long., -2.7^{o} Lat.
Direction of right rod	62.9^{o} Long., 1.5^{o} Lat.

Finally, additional analysis focused on the sizing of the springs needed to **extend** the tail and to **expose** the micro rovers by lifting the nose of glider. Instrumentation and system mass for the micro rovers were specified and rough packaging analyses were completed for the glider.

<u>Priority technical challenges / questions to be addressed:</u>

1. Parametric design of glider lifting and control surfaces;
2. Building a proof-of-concept prototype of the spherical linkage;
3. Explore architecture of base component and validate rocket launch phase of mission;

3.4 Final discussion on concept development

The work completed in this section allowed for initial parameters of system architecture to be explored. While individual components can be modeled at this phase of design, measuring system performance across chaotic terrain requires a system-level simulation. The challenges of designing a rover architecture for mobility in rugged and uncertain terrain poses an optimization problem with a necessarily stochastic component. Specifically returning to the concept defined in Section 3.2, it was stated that a model that includes the interaction of the spherical rover with the terrain in 'free rolling' and the ability to describe the impact of the actuated legs was required.

However, working toward this goal requires new techniques for assessing more complex forms of reconfigurability. The next section of this report addresses several key challenges in assessing reconfigurability by using hi-fidelity simulations to collect three different performance measures of a Mars rover traversing chaotic terrain. These performance measures are then combined into a single performance score to facilitate architecture selection between a traditional rover design and the concept outlined in Section 3.2

4. Development of techniques to facilitate architecture determination

This section presents a strategy for assessing the effectiveness of an architecture transformation when chaotic terrain is considered. A hi-fidelity simulation environment is used to quickly run a myriad of test scenarios on the concept developed in Section 3.2 and a traditional rocker-bogie architecture. Four rovers – two architectures using two size scales - are tested in twenty terrain challenges, and their performance will be explored across various levels of ground traction, slope, and rock field density. By considering potential missions as a combination of the objectives of the terrain challenges, architecture selection is explored.

4.1 Simulation environment

Webots is a commercial robotics package used in this research to conduct virtual simulations of proposed system operation (Webots 2012). Effective simulation allows comparative studies of complex systems to be conducted without the need for the significant investment required for scale prototyping. Traditionally, simulations of highly complicated rovers are limited to the detailed kinematics and control schemes that are involved in the operation of a single rover type (Yim et al. 2000, Grand et al. 2002, Schmidt-Wetekam et al. 2007). Webots was chosen because it offers large scale simulation capabilities using simplified models of rover architectures. The models include simulated servomotors, actuators, cameras, and sensors, while the physical interactions of the robot with its environment are handled by the Open Dynamics Engine (ODE), an open source library of code for simulating rigid body dynamics (ode 2012).

Simulation allows for a higher level investigation of a system than analytical modeling and testing that is not possible or feasible for high fidelity prototypes. The gravity vector can be changed to its value at the Mars Orbiter Laser Altimeter datum, $3.711 m/s^2$. This allows the rovers to be tested in an environment that approximates the one in which they would actually operate. Furthermore, driving a complex prototype off a large rock on a steep incline is an expensive proposition. It can be done easily and repeatedly in Webots without dealing lasting damage to the simulated rover.

4.2 Experimental setup

Two rover designs are compared in this study: a traditional rocker-bogie architecture and a multi-ability reconfigurable architecture based on the TRREx design. Full models of these rovers were created in Webots, and a variety of trial environments were created to test the rovers along a straight line course. The environments were 8 m wide and 25 m long. The rovers were started 2.5 m along the length and in the center of the width. They were pointed at a target 20 m directly ahead. This approach allowed assessment of each architecture's innate characteristics without complicating the analysis with varying levels of control complexity and sophistication. Performing the analysis in this open loop analysis will later provide an indication of how much control would be needed to make each architecture viable in different scenarios. In future work, control complexity may be added to the analysis and treated as a cost variable.

For the full size case, the rocker-bogie rover was modeled to be the same size as the Curiosity rover: approximately three meters from the front wheel to the back and three meters wide. The TRREx concept was scaled to be approximately the same size as the rocker-bogie model so that it would behave similarly in the terrain. The roving mode of the TRREx is thus approximately 3m from front wheel to rear wheel and 2m across at the wheels. At this scaling, the TRREx ball mode is a 1m sphere. The sphere used was solid rather than hollow on the assumption that the mass of computer and instruments at the center of the rover would make it behave more like a solid sphere. Having the models be on the same order in size also means that they can be assumed to have similar mass and cost requirements. In future work, the assessment should include measuring mass and cost tradeoffs.

Since the focus on developing better rovers so far has involved increasing size, another variation considered was identical rovers of different sizes. Both models were tested at full scale and at half scale in an effort to determine the effect of size on performance. In practice, it was easier to change the size of the environments than to scale the rovers. Therefore, the rock fields were doubled in size for the half scale tests and distances were then halved in the analysis.

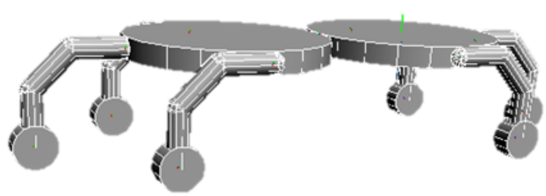


Figure 30. The TRREx testing model used in Webots

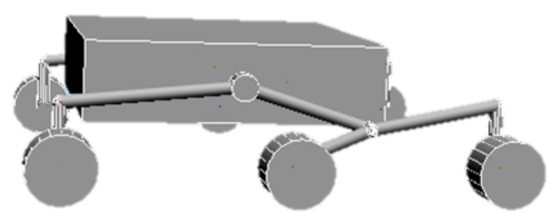


Figure 31. The rocker bogie testing model used in Webots

<u>Terrain characteristics:</u>

Twenty test scenarios were created by enumerating the three terrain variables shown in Table 9: angle of ascent/decent, traction, and rock field density. The slope variable refers to the angle the ground makes with a plane perpendicular to the gravity vector. The rover starts pointed straight up (or down) the slope of this hill. While local anomalies may create small features with steeper than 30° slopes, according to several studies, the soil characteristics on Mars suggest that it is unlikely that large features with uniformly steeper slopes exist (Perko et al. 2006). Since a fully capable robot could navigate around a localized trouble spot, this investigation was bounded to slopes within ±30°.

Table 9. Terrain parameters

Level	Slope	Rock Field	Friction
1	30^0 Uphill	Sparse	High
2	15^0 Uphill	Dense	Low
3	0^0		
4	15^0 Downhill		
5	30^0 Downhill		

Golombeck and Rapp provide the most widely cited model describing the distribution of rocks on Mars (1997). They model a rock field as follows:

$$N(D) = Le^{-sD} \quad [6]$$
$$F(D) = ke^{-qD} \quad [7]$$

In Equation 6, N is the cumulative number of rocks per square meter with a diameter greater than or equal to a given diameter, D (in meters). F is the cumulative fractional area covered by rocks with diameter greater than or equal D. L, s, k, and q are constants that can be fit to the data of any particular rock field.[8]

Equation 7 is a model for correlating between different types of global and local data such as thermal inertia data from orbital measurements and rock field observations by rovers. This is not as useful as Equation 6 for generating terrain. For this reason, terrain generation used Equation 6 to model a diameter distribution based on given input parameters L, s, the dimensions of the desired field, and the slope angle. A Matlab code was developed to randomly assign diameters and locations to rocks that would follow this distribution. Rocks were modeled as spheres with their centers lying in the plane of the sloped ground.

The "sparse" field uses the fit for the Viking 2 lander site: $L=6.84$, $s=8.3$. The "dense" field uses the fit for Mars Hill, a testing site in Death Valley, CA which is quite rugged in comparison: $L = 4.78$, $s = 3.06$. In this case, sparse and dense are relative terms, as the VL2 site is believed to be amongst the rockiest places on Mars while Mars Hill is most likely more rugged than any site anywhere on Mars. Such rugged fields were chosen in the spirit of testing a chaotic terrain.

The same rock field was used for all of the trials of a certain type, as shown in Table 10. That is, the rock field in trial 2 is the same as the rock field in trial 1. Likewise, in trial 5, the same rocks were used. Their height (y-axis coordinate) was reassigned so they would lie in the 15^o plane instead of the 30^o plane. In this way, the data accurately depicts the difference between 30^o and 15^o without adding variation from stochastic rock locations.

A soil model accounting for sinking and slipping was desired for this investigation. Webots is a powerful tool for rover design, control, and simulation; however, it is configured mostly around rigid body assumptions. It is not particularly well equipped to model deformable terrain. Therefore the ground interaction variable only includes a slipping model but not a sinking model. Soil strength is often modeled starting with Equation 8.

$$\tau_{max} = c + \sigma \tan\phi \qquad [8]$$

τ_{max} is the maximum shear stress the soil can sustain. c is the cohesitivity, σ is the normal stress on the soil, ϕ is the soil's friction angle. Since sinking was not considered and Martian soil has very low cohesitivity, c can be neglected. Rearranging the terms:

$$C_f = \frac{\tau}{\sigma} = \tan\phi \qquad [9]$$

In Equation 9, C_f is the friction coefficient which can easily be modeled in Webots. Two values of ϕ were chosen for the ground-wheel interaction. "Low" friction is modeled as $C_f = \tan(17^o)$. This is in the range given for dust deposits. "High" friction is modeled as $C_f = \tan(38^o)$ which is consistent with dust overlying rock.[20]

Creating all possible combinations of the three variables yields 20 scenarios, as listed in Table 10. Figure 32 shows several sample screenshots of the terrains. Note, at least four of these scenarios are so unlikely to occur as to be physically unrealistic. Soil with an internal friction angle of 17^o would never be expected to form a slope of 30^o. Thus trials 2, 4, 18, and 20 are not expected to represent real world trials. As will be shown in the results, the rover behaved as poorly as expected in those situations. They were included for completeness.

Table 10. Trial specifications

Trial #	Slope	Rocks	Friction	**Trial #**	Slope	Rocks	Friction
1	30^0	Sparse	High	**11**	0^0	Dense	High
2	30^0	Sparse	Low	**12**	0^0	Dense	Low
3	30^0	Dense	High	**13**	-15^0	Sparse	High
4	30^0	Dense	Low	**14**	-15^0	Sparse	Low
5	15^0	Sparse	High	**15**	-15^0	Dense	High
6	15^0	Sparse	Low	**16**	-15^0	Dense	Low
7	15^0	Dense	High	**17**	-30^0	Sparse	High
8	15^0	Dense	Low	**18**	-30^0	Sparse	Low
9	0^0	Sparse	High	**19**	-30^0	Dense	High
10	0^0	Sparse	Low	**20**	-30^0	Dense	Low

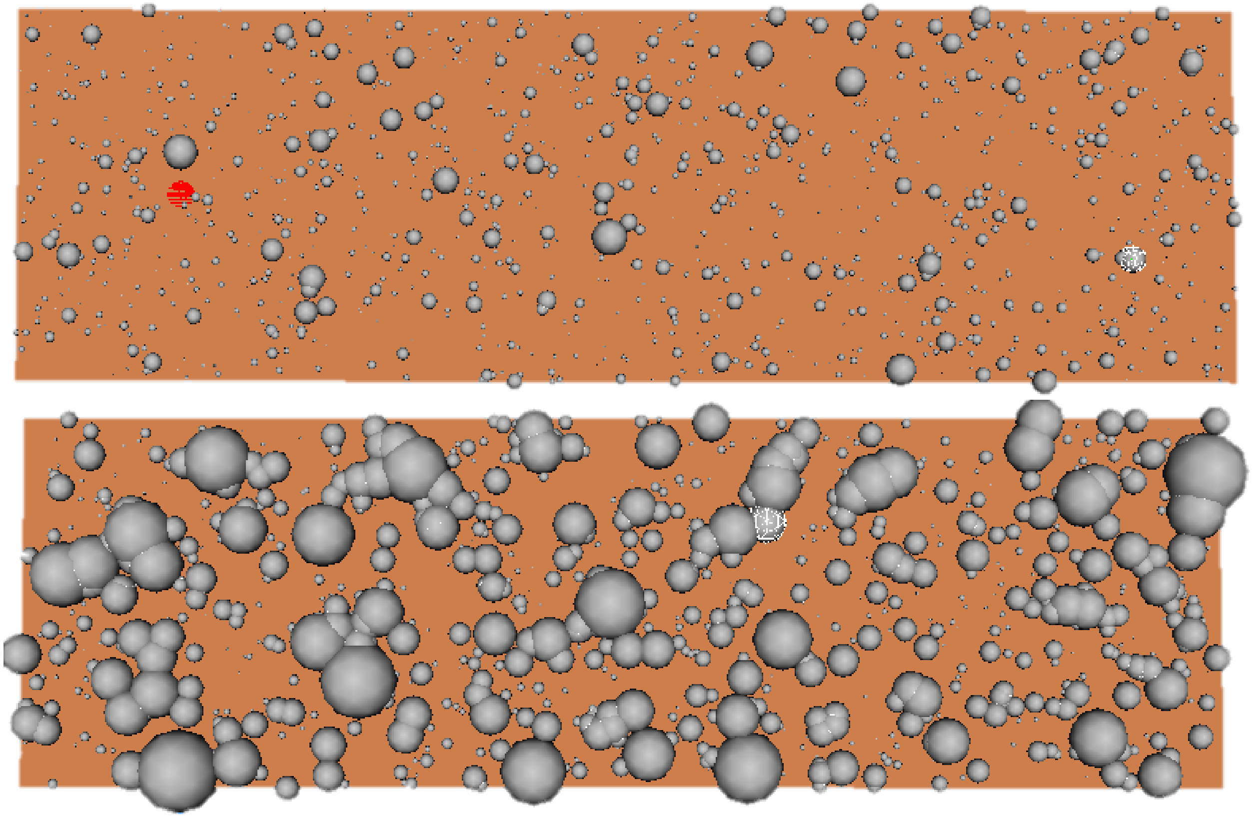


Figure 32. Examples of the sparse (above) and dense (below) rock fields used in the rover testing

Experimental process:

Both rovers were operated such that on flat ground they would be moving at a constant 2.5 cm/s. This is representative of a mid-range speed for Mars rovers, although they are usually operated closer to 1 cm/s since large parts of their control is done on Earth. The simulation output provided the rover's location every 10 seconds. Rovers were evaluated in terms of average speed, deviation from a straight line path, and mean free path length.

In several cases, a rover would completely fail a trial. One scenario typical for both rovers was that its orientation was disrupted as it attempted to navigate the rock field and exited the field on one side or the other rather than traversing all the way to the target. This failure mode could be avoided in future testing by making the rock fields arbitrarily large. However, this scenario is indicative of a disruption sufficiently large that a command input would be required to return the rover to its desired path. Thus for the purpose of this research it is useful to treat it in the same way as the other failure modes. A rover would sometimes be able to partially surmount an obstacle only to have its body get hung up and prevent it from moving. The rover might manage to pull itself free from such a situation, but it is likely that this process would cause severe damage to a rover. Another common failure involved the rover encountering an obstacle it simply could not overcome, especially for the smaller rover architectures. Finally, friction with the ground was sometimes insufficient for the rover to make forward progress uphill or to prevent an uncontrolled downhill slide. When any of these failures occurred, a note was made in the data sets and the rover was manually moved past the obstacle. This allowed the rover to be evaluated across multiple sections of the rock fields instead of only the small distance before first failure.

Performance measures:

Several performance characteristics were calculated from the raw Webots data output. In some trials, the obstacles would cause a failure that would end the trial. In other trials, the rover was made it all of the way to the target with only minor course disruptions caused by the various obstacles. Three performance measures that describe both cases were chosen, and they are discussed in this section. A description of how the various measures were used to inform the architecture selection is also provided.

The most basic description of performance is "How far did the rover go?" This is answered by the "first stop" (FS) metric. Mathematically, this is described as the straight line distance from the start point to the point that the first rover failure occurred. This metric is highly susceptible to a "luck" factor. While the distribution of the obstacles provides some expectation as to how far the rover should go, a large rock in front of an initialized rover can end a trial before much data is collected.

To overcome the limitations of the FS metric, a rover encountering a failure would be reset and moved over the obstacle causing the failure. The trial would resume from there. This would continue for several restarts (at the discretion of the tester) or until the rover passed the target. The data was broken into forward progress segments by selecting points out of the data representing when the rover started and stopped. In this way, multiple trials were performed of the first stop measurement.

Mean free path (MFP) is defined as "expected distance that the vehicle can travel in a straight line before it encounters a non-traversable hazard." Patel, N. et al have used this measure to classify the rover's intrinsic ability to overcome obstacles (2004). Often MFP is calculated analytically based on the rock distribution and some index rock size that a rover cannot overcome. In this study, it was measured directly as the average of several trials' FS measurements. This allows the terrain to determine what causes the stop, rather than an analytical failure model. The benefit is the arrangement of rocks sometimes allows the rover to overcome an obstacle that an analytical derivation would assume to cause a failure. The drawback is that with the limited number of simulations, the MFP measurements are susceptible to noise.

The mean free path ratio (MFPR) is the ratio of MFP to the diameter of the rover's minimum turning circle. It can assess how sophisticated the navigational control of a rover must be. If the MFPR is much bigger than one, the rover should need only occasional course corrections and high-level navigation inputs. If the MFPR is much smaller than one, the rover is incapable of navigating in the terrain under consideration. For a rover with MFPR near one, mobility is possible but requires detailed sensing and sophisticated navigational control (Patel et al. 2004).

In the case that the rover made it to the target, the MFP was assigned as 20m for the sake of assigning a score to the trial. This is necessary because the simulation cannot run forever so some limit must be imposed. The large rocker bogie rover has a turning diameter near 5.6m. So if it travels 20m without a failure, its MFPR is greater than 3.5. Thus, the rover is pretty capable compared to the terrain and running it further to get an exact number is a low value use of simulation time.

Another measure of the rover's performance was the Root Mean Square Distance from the Path (D_{rms}). It is calculated for each data point as follows:

$$D_{z,rms} = \sqrt{mean\left(\left(z_{rover-}z_{path}\right)^2\right)} \qquad [10]$$

Where z_{rover} is the coordinate of the rover left/right of its intended travel direction and z_{path} is the location of the straight line from the start to the finish. D_{rms} provides a different measure of control input required. It characterizes how much the ground moves the rover away from its desired straight path. One problem arises with this measure for the case that the rover gets stopped. Each time the rover trial is restarted, the rover returns to the desired path. For that reason, this data is normalized against the MFP. Thus, a D_{rms}^* becomes the ratio of how far the rover moves sideways to how far it moves forward. The multiplied scalar sizes the measure to a value that is easier to read. As shown in Equation 11, D_{rms}^* is the normalized root mean square distance from the path measurement.

$$D_{rms}{}^{*} = \frac{10 * D_{z,rms}}{MFP} \qquad [11]$$

Finally, average speed (V_{avg}) was calculated across the trial, as shown in Equation 12. The rovers were all set to run at the same speed in each trial, so this is a measure of how the rock field hinders the rover's forward progress. For each forward progress segment of the trial, the distance between start and end point is calculated. Because the data points were recorded at a regular interval, the elapsed time can be easily found.

$$V_{avg} = \frac{\sum D_{segment}}{\sum t_{elapsed}} \qquad [12]$$

Performance measure compilation:

Hazelrigg's decision based design describes a decision making approach using utility curves to represent strength of preference (SoP) in mapping some system characteristic to a non-dimensional utility score (1998). Then the various utility scores are added, with a weighting to determine an overall system utility score, as shown in Equation 13:

$$U_j = \sum_i W_i u_{i,j}\left(x_{i,j}\right) \qquad [13]$$

where U_j is the utility of the j^{th} alternative, w_i is the weight of the i^{th} performance characteristic, $x_{i,j}$ is the level of the i^{th} performance characteristic of the j^{th} alternative and $u_{i,j}$ is the non-dimensional utility as a function of $x_{i,j}$ (See and Lewis 2002)

For this investigation, it is assumed that the designer's SoP curves are known. The three performance measures, MFPR, D_{RMS}^*, and V_{avg}, are mapped to utility measures according to the assumed SoP curve. Then the utility for each rover trial was compiled based on some assumed weights. In this way, a selection of the best architecture for a given trial can be made in a mathematically rigorous and repeatable way. Several hypothetical missions were envisioned and evaluated as a combination of the scenarios from the twenty trials. An investigation was done to explore the effect of different weighting structures on the final architecture decision. The utility score for a hypothetical mission was taken to be the time weighted average of the utility scores of the constituent missions.

4.3 Results

Shown in Figures 33, 34, and 35 are several rover trajectories plotted from the position data returned by the rovers. The vertical axes in the charts correspond to distance in meters traveled down the intended path, the horizontal axis is distance left and right along the path. In Figures 33 and 34, each point represents ten seconds of elapsed simulation time. In Figure 35, each point represents one second of simulation time. Similar plots were formed for all twenty trials for each of the four rovers.

Table 11 presents the Best and Worst Performance in each of the three performance categories:

Table 11. Performance ranges.

Objective	Best Observed	Worst Observed	U =1	U = 0
MFPR	20	0.05	3.5	1
Drms*	0.045	60.5	0	20
Vavg, flat/up	0.025	0.002	0.025	0
Vavg, down	2.66	0.01	2.7	0

Various techniques exist to determine a designer's strength of preference (Hazelrigg 1998). These techniques may be applied to future work. For the sake of this report, linear strength of preference curves are used as the default. To derive the linear relationship between performance characteristic and utility, one must only assign the value of the performance characteristic that correspond to maximum utility and minimum utility which have values of one and zero, respectively. These assignments are shown in the right two columns of Table 11. In most cases maximum utility is set near the best observed measurement. Lowest utility is set near the lowest observed measurement.

For MFPR, a score of 1 was given the lowest utility. This is because, as explained above, rovers with MFPR = 1 are capable of maneuvering but require sophisticated control. For rovers with MFPR between 0.8 and 1, a utility of zero was also assigned. As a MFPR score less than 0.8 describes a rover that is not sufficiently maneuverable to perform the task, rovers receiving this score were treated as an infeasible choice for that task. This is consistent with Patel et al.'s categorization of MFPR (Perko et al. 2006).

The D_{rms}^* utility was bounded at the high end by 20. A rover that performs worse than this (has a higher score) deviates drastically from its assigned path and therefore provides no utility due to its inability to stay on the path. All measurements greater than 20 were assigned zero utility.

Two curves were used for V_{avg} because two distinctly different speed regimes existed. The flat and uphill data were limited by the forward speed of the rover. The downhill speed range had much higher potential due to the freely rolling TRREx in ball mode. Therefore, a flat/uphill utility curve is used for the flat trials (trials 9-12) and the uphill trials (trials 1-8) while a downhill utility curve is used or the downhill trials (trials 13-20).

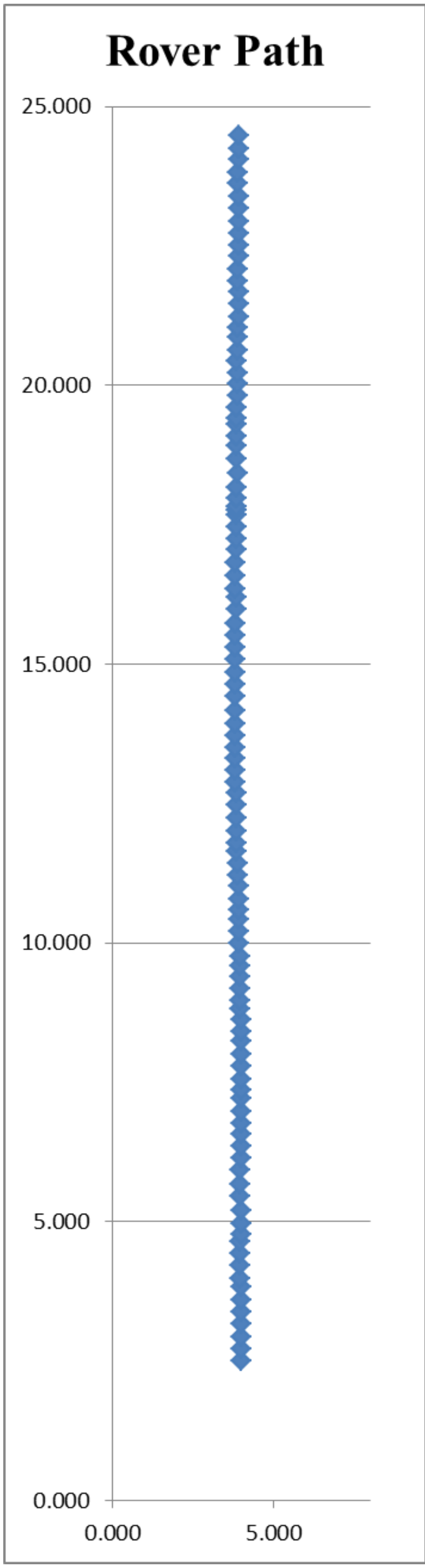


Figure 33. Large Rocker Bogie: Trial 6

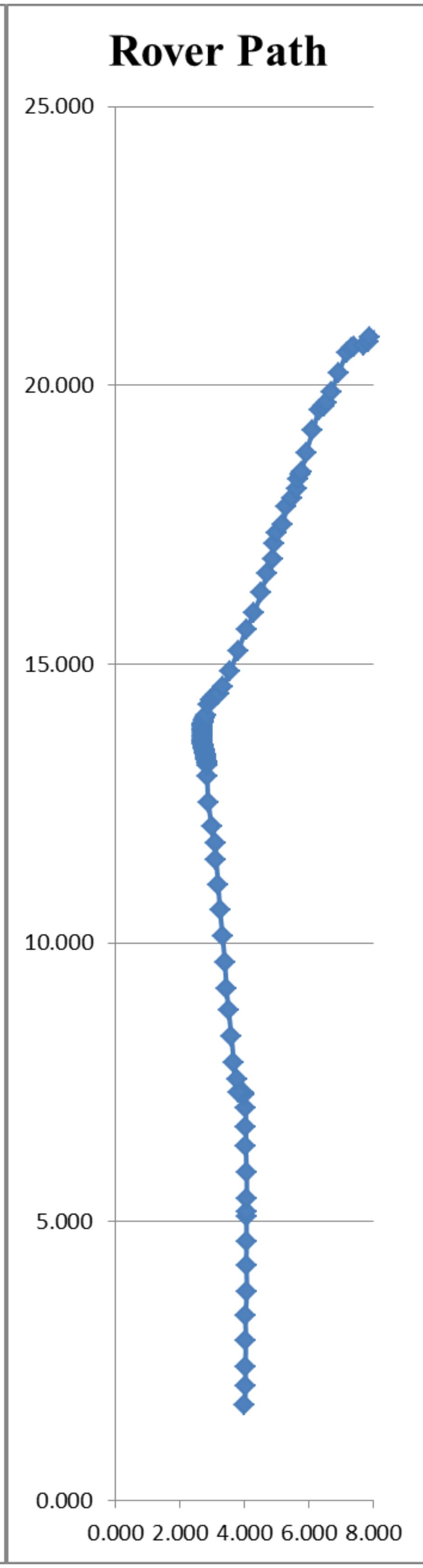


Figure 34. Large TRREx: Trial 10

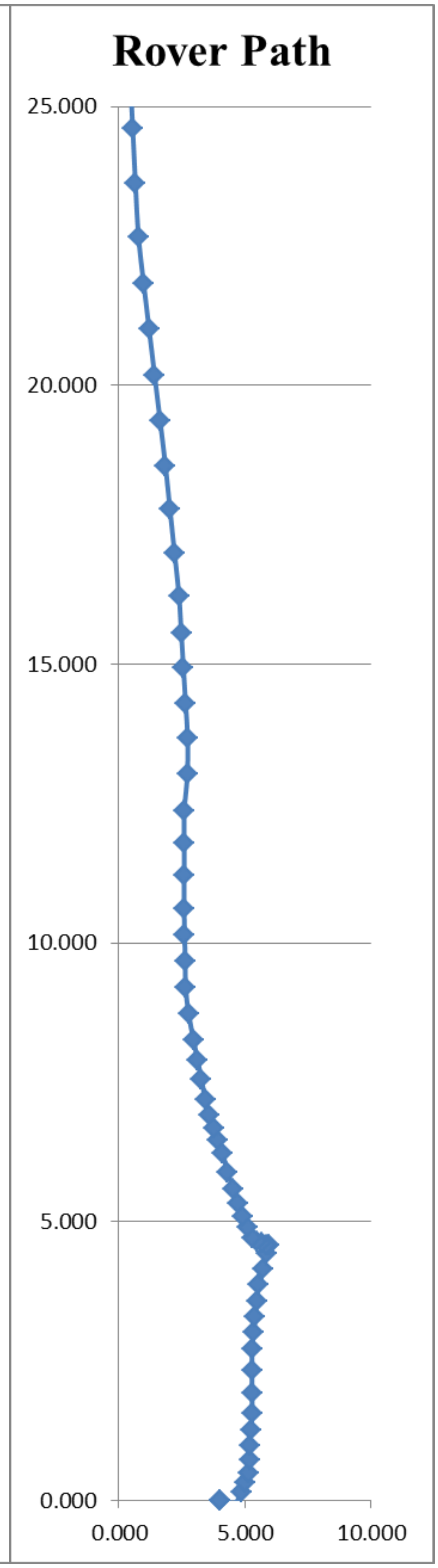


Figure 35. Large TRREx: Trial 13, Ball mode

4.4 Analysis

Weighting study:

Table 12 shows the results of the best rover for each mission under varying performance weightings. The first column is treated as a baseline with equal weighting in all three categories. Variations from the baseline are highlighted. Clearly, no particular rover shows up as the best in all cases. The Large RB is consistently the best for flat ground. Small rovers are often preferred for hill climbing due to their short turning radiuses, giving them a boost in MFPR. In many of the uphill trials, only a few rovers could be considered viable candidates. The TRREx rovers demonstrate significant potential on the downhill portion, as the reconfiguration into ball mode allows a high performance in the V_{avg} category. Varying the weights has very little effect on the outcomes except in the case that speed is neglected entirely which removes the advantage the TRREx rovers have on the downhill trials.

Table 12. Weighting study results

	Weighting					
U_{mfpr}	0.333	0.500	0.333	0.333	0.500	0.000
U_{drms}	0.333	0.167	0.167	0.500	0.500	0.000
U_{vavg}	0.333	0.333	0.500	0.167	0.000	1.000
Trial	Best Rover					
1	Sm. TRREx	Sm. TRREx	Sm. TRREx	Sm. TRREx	Sm. TRREx	Sm. TRREx
2	Sm. RB	Sm. RB	Sm. RB	Sm. RB	Sm. RB	Sm. RB
3	Sm. RB	Sm. RB	Sm. RB	Sm. RB	Sm. RB	Sm. TRREx
4	None	None	None	None	None	None
5	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. RB
6	Sm. RB	Sm. RB	Sm. RB	Sm. RB	Lg. RB	Sm. RB
7	Sm. TRREx	Sm. TRREx	Sm. TRREx	Sm. TRREx	Sm. TRREx	Sm. TRREx
8	None	None	None	None	None	None
9	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. RB
10	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. TRREx
11	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. RB
12	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. RB
13	Sm. TRREx	Sm. TRREx	Sm. TRREx	Sm. TRREx	Lg. RB	Sm. TRREx
14	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. RB	Lg. TRREx
15	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. RB	Lg. TRREx
16	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. TRREx
17	Sm. TRREx	Sm. TRREx	Sm. TRREx	Sm. TRREx	Lg. RB	Sm. TRREx
18	Sm. TRREx	Lg. TRREx	Lg. TRREx	Sm. TRREx	Sm. TRREx	Lg. TRREx
19	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. RB	Lg. TRREx
20	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. RB	Lg. TRREx

Mission study:

So far the terrains have been handled as homogenous terrains with assigned characteristics. In this section the various task scores will be combined into missions comprised of a variety of terrain types. Four hypothetical missions were envisioned to demonstrate how task-wise data can be combined to provide an architecture selection for a more realistic rover mission. Here another set of weightings is assigned to represent the importance of a rover's performance in the various tasks to the performance in the overall mission. The utility score of the rover for the hypothetical mission is defined as the weighted sum of the task utilities. The four missions are described as follows:

Mission 1 "Basic": This mission is mostly flat sparse terrain with mildly varying slope, friction, and a small amount of rugged terrain.

- 50% task 9: flat, high friction, sparse rocks
- 10% task 5: 15^o uphill, high friction, sparse rocks
- 10% task 10: flat, low friction, sparse rocks
- 10% task 11: flat, high friction, rugged rocks
- 10% task 13: 15^o downhill, high friction, sparse rocks

Mission 2 "Hills": This mission is entirely hills with nearly equal amounts uphill and downhill. A sampling of rugged/sparse and high/low friction was chosen.

- 25% task 3: 30^o uphill, high friction, rugged rocks
- 15% task 5: 15^o uphill, high friction, sparse rocks
- 5% task 6: 15^o uphill, low friction, sparse rocks
- 15% task 13: 15^o downhill, high friction, sparse rocks
- 5% task 16: 15^o downhill, low friction, sparse rocks
- 25% task 17: 15^o downhill, high friction, rugged rocks
- 10% task 19: 30^o downhill, high friction, sparse rocks

Mission 3 "Rugged": This mission is flat and mild slopes but with rugged rocks in all parts. It is mostly high friction but a few scenarios with low friction are mixed in.

- 30% task 7: 15^o uphill, high friction, rugged rocks
- 25% task 11: flat, high friction, rugged rocks
- 10% task 12: flat, low friction, rugged rocks
- 25% task 15: 15^o downhill, high friction, rugged rocks
- 10% task 16: 15^o downhill, low friction, rugged rocks

Mission 4 "Going Down": This mission is a mix of downhill scenarios:

- 25% task 13: 15^o downhill, high friction, sparse rocks
- 25% task 15: 15^o downhill, high friction, rugged rocks
- 25% task 17: 30^o downhill, high friction, sparse rocks
- 25% task 19: 30^o downhill, high friction, rugged rocks

The performance weightings were set to the baseline of 1/3 for each of the three measures. The resulting scores are shown in Table 13 with the highest utility highlighted for each mission.

Table 13. Hypothetical missions

Mission 1 "Basic"	
Large RB	0.807
Large TRREx	0.674
Small RB	0.740
Small TRREx	0.730

Mission 2 "Hills"	
Large RB	0.551
Large TRREx	0.619
Small RB	0.716
Small TRREx	0.672

Mission 3 "Rugged"	
Large RB	Insuf
Large TRREx	Insuf
Small RB	Insuf
Small TRREx	0.511

Mission 4 "Going Down"	
Large RB	0.666
Large TRREx	0.830
Small RB	0.571
Small TRREx	0.776

The results of missions one, three, and four are obvious. Mission one is largely comprised of flat terrain where large rocker bogies demonstrated proficiency. The Small TRREx is the only viable solution to trial 7 which is one of the components of mission 3. Thus it is the only viable rover for mission 3. The TRREx rover is designed specifically to have an advantage going downhill. The weighting study validated that it is favorable for downhill travel. Thus it is obvious that the TRREx rovers take the first and second spots in mission 4.

Mission two provides some deeper insights. The small rocker bogie is the ultimate winner. However, if a larger rover is desired for other design considerations, the TRREx architecture is better in the large category. This is useful information for a prospective designer. Furthermore, the small TRREx score is close to the small RB score. Therefore, mission two is a good candidate for another weighting study. In Table 14, the weights were shifted toward speed (.333 MFPR, .167 D_{rms}^*, .5 V_{avg}). This switches the best choice from the small rocker bogie to the small TRREx.

Table 14. Mission two weighting study

Mission 2 "Hills" Baseline	
Large RB	0.551
Large TRREx	0.619
Small RB	0.716
Small TRREx	0.672

Mission 2 "Hilly" Reweighted	
Large RB	0.453
Large TRREx	0.571
Small RB	0.589
Small TRREx	0.603

The weighting study showed that the selection of a rover for a particular task is insensitive to the weighting structure used. However, the mission study demonstrated that when the tasks are combined into a more complex mission, a small change to the weighting structure may cause a change in architecture choice. Since the biggest advantage provided by the TRREx is its increase in downhill speed, certainly any mission in which it is preferred to a rocker bogie must include some opportunity for it to roll downhill. This analysis demonstrates that the designer must also care sufficiently about speed or the rocker bogie will still be preferred.

4.5 Discussion and conclusions

Hi-fidelity simulation is demonstrated as a highly useful tool for investigating reconfigurable architecture selection in a chaotic performance environment. Webots provided the capability to model all aspects of the rovers and terrain. A framework for performance measurement was established using utility based decision theory. Sensitivity studies on the weighting of performance measures demonstrated clear architecture selection for a given task. The mission study provided a framework for relating task performance to broader mission goals. The mission two sensitivity studies illustrated the tradeoffs inherent in picking just one rover to do a mission of multiple tasks. The designer's decision about speed vs. maneuverability changed the best architecture choice.

The analyses provide insight into the relative strengths of the four designs in a variety of scenarios. The TRREx rover generally underperforms the rocker bogie at traditional rover tasks. This is largely because the rover's ability to reconfigure to ball mode imposes substantial constraints on the architecture of its rover mode. A smaller effect may be due to excessive simplification of the algorithms running the active suspension controller. The ability to transform gives the TRREx a distinct and significant advantage over the rocker bogie rover when it is used for downhill travel. Thus, a decision to pick the rocker bogie or the TRREx for a given mission would have to be based on the mission profile, taking into account the likely terrain that would be encountered. The hypothetical mission investigation validates this expectation. Mission four which requires a significant amount of downhill travel, favors the TRREx rover. A mission consisting mainly of flat and uphill travel, such as missions one and two would favor the rocker bogie system. The selection of weights is shown to have minimal impact on which rover is best for a given task as shown by the weighting investigation results.

The size parameter indicates that large rovers are good for relatively benign terrain. However, small rovers may be better for very rugged scenarios as their shorter turning diameters may allow them to navigate around rocks that are too big for even big rovers to cross. Size may not always be a choice. The criteria for payload weight and size may require a large rover. This investigation showed that if this is the case, the decision between rocker bogie and TRREx may be a function of the size of the rover as the analysis of mission two showed.

Avenues for related future works include:

- Improving the sophistication of the TRREx active suspension controller could improve the reliability of the investigation.
- Various improvements to the simulation fidelity may include using more realistic rocks with varied geometries and heights above the plane and/or a ground interaction model that includes a sinking failure mode.
- Testing the rovers in a larger field could allow a longer MFP assignment to a rover that makes it to the target. This would allow the MFPR of the large rocker bogie to be higher than 3.5 so the utility curve of MFPR could be extended out to larger amounts. In this way, the relative ranking of the rovers in the MFPR category may change as the large rocker bogie is allowed to close the gap on the more maneuverable rovers.
- Varying the weights does not drastically effect the selection for each task. It would be interesting to see if it changes the choice when the tasks are compiled into hypothetical missions. For example, mission two shows the small TRREx as a close second. Perhaps increasing the weight on velocity would cause this selection to swap.

- An investigation into varying the strength of preference curves might be interesting. Conversely, working with a subject matter expert to model realistic strength of preference curves could improve the predictions made by this model.
- Future efforts should address more assessment criteria of the system including cost, control complexity, various risk measures, etc.
- As the model increases in complexity better visualization tools may be needed to illustrate the inherent trade-offs.
- This investigation that using a small maneuverable rover improves MFPR scores and makes it desirable in the rugged terrain. Increasing rover size may allow the rover to surmount more obstacles; the conventional wisdom says make the rovers bigger to increase mobility in rock fields. An interesting study might make even bigger rovers—perhaps 150% scale to the large rovers in this study—to see if increasing the size also improves performance by increasing the numerator of the MFPR calculation.

5. Dissemination

Results from this proposal, specifically those reported in Section 4, were published and presented at the 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference held in Indianapolis, Indiana. An abstract further developing the high-fidelity simulations for system-level performance estimation has been submitted to the 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Material Conference (9th AIAA MDO Specialist Conference) to be held in Boston, Massachusetts in April 2013. Development of the TRREx rover architecture (discussed in Section 3.2) was published and presented at the 63rd International Astronautical Congress in Naples, Italy.

We have plans to publish the outcomes from the systematic study (Section 2) at the 2013 ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. We will also work to publish two journal papers based on this research.

6. Conclusions and future research direction

Effective large-scale exploration of planetary surfaces requires robotic vehicles capable of mobility across chaotic terrain. To date, rovers sent to Mars have been based on the standard "rocker-bogie" style architecture, and hence have been limited to exploring relatively flat, even terrain. In search of "game-changing" technologies that can enable robotic exploration of much more challenging terrains, we have examined the role that transformation principles can play in facilitating the development of such technologies.

As part of this effort we made use of three senior design teams to generate new ideas, and also employed three graduate students who worked in this area as part of their thesis and class work. The basic strategy we employed was to:

- generate configuration changes using transformation principles (e.g. using brainstorming);
- identify promising concepts that use transformation to explore different types of terrain;
- create virtual and physical prototypes;
- develop analytical models describing system motion and function over randomly generated random terrain profiles;
- and, conduct a quantitative evaluation of system performance.

After analyzing 31 concepts, a pattern emerged; namely that the most fruitful transformation principles for planetary rover exploration are expand / collapse and expose / cover. Fuse / divide was also found to be useful, but this is not new, as NASA has been using this principle for over 40 years. Additionally, while reorientation can enable game-changing architecture changes when combined with other transformation principles, it does so from a secondary support role.

In addition to identifying the most promising transformation principles, we also chose to develop three system architectures: a glider/base system for exploring Mars' Melas Chasma, an Air Cannon system for exploring Mars' Valles Marineris, and a transforming Roving-Rolling Explorer (TRREx) for exploring Mars' Hellas Basin. While this development mostly occurs to validate initial concept feasibility, we also present a strategy for assessing the system-level effectiveness of architecture transformations in the presence of chaotic terrain. A hi-fidelity simulation environment is used to quickly run a myriad of test scenarios on the TRREx concept and the traditional rocker-bogie architecture. Four rovers – two architectures using two size scales - are tested across various levels of ground traction, slope, and rock field density. Utility theory is combined with identified performance measures to explore rational architecture selection across potential missions generated as a combination of terrain challenges. From this study, we conclude that architecture decisions for a given mission must be based on mission profile, terrain encountered, and the size of the rover to be deployed.

In summary, we have used this Phase I effort to engage in a very broad exploration of concepts enabled by system transformation, identified the concepts of expand/collapse and expose/cover as being particularly promising with respect to developing game changing architectures for planetary exploration, have performed detailed development and analysis of three particularly promising technologies, and have developed techniques for evaluating the performance of these new concepts with respect to how well they can achieve desired exploration goals over rough and chaotic terrains.

While this study has explored the design space enabled by transformation principles, future efforts must characterize and explore the tradespace for specific architectures. Fundamentally, this requires the aggregation of information from the engineering and mission science disciplines. This will require appropriate measures of risk, complexity, and performance to be explored within existing decision-making frameworks developed by the engineering design community. Additional efforts must be undertaken to identify the key technologies that need to be created, improved, or adopted if the proposed architectures are to be further matured.

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